Ion Beam Source Construction and Applications

Presented by

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ABSTRACT

The aim of this thesis is to improve the performance of a new shape cold cathode Penning ion source to be suitable for some applications.

In this work, many trials have been made to reach the optimum dimensions of the new shape of cold Molybdenum cathode Penning ion source with radial extraction. The high output ion beam can be extracted in a direction transverse to the discharge region.

The new shape cold cathode Penning ion source consists of Copper cylindrical hollow anode of 40 mm length, 12 mm diameter and has two similar cone ends of 15 mm length, 22 mm upper cone diameter and 12 mm bottom cone diameter. The two movable Molybdenum cathodes are fixed in Perspex insulator and placed symmetrically at two ends of the anode. The Copper emission disc of 2 mm thickness and has central aperture of different diameters is placed at the middle of the anode for ion beam exit. The inner surface of the emission disc is isolated from the anode by Perspex insulator except an area of diameter 5 mm to confine the electrical discharge in this area. A movable Faraday cup is placed at different distances from the emission electrode aperture and used to collect the output ion beam from the ion source.
The working gases are admitted to the ion source through a hole in the anode via a needle valve which placed between the gas cylinder and the ion source.

The optimum anode- cathode distance, the uncovered area diameter of the emission disc, the central aperture diameter of the emission electrode, the distance between emission electrode and Faraday cup have been determined using Argon gas. The optimum distances of the ion source were found to be equal to 6 mm, 5 mm, 2.5 mm, and 3 cm respectively where stable discharge current and maximum output ion beam current at low discharge current can be obtained.

The discharge characteristics, ion beam characteristics, and the efficiency of the ion source have been measured at different operating conditions and different gas pressures using Argon gas. The ion source characteristics are measured at the optimum operating conditions using Argon and Nitrogen gases. The effect of negative voltage applied to Faraday cup on the output ion beam current is determined.

The effect of permanent magnet on the discharge characteristics of the ion source has been determined. An axial Samarium- Cobalt permanent magnet of intensity, B, is used. The optimum permanent magnet - anode distance is equal to 1.5 cm which obtain from many trials.
The energy of the heavy charged particles in this plasma of the ion source is measured using energy analyzer system. The retarding of ions can be determined by applying positive voltage on the retarding grid and from the experimental results, the energy distribution can be obtained.

The efficiency of ion source can be determined using Nitrogen and Argon gases. The perveance of the ion source can be calculated from the experimental data of Argon and Nitrogen gases. The operating time of this ion source can be determined during the exposure of Argon gas on Molybdenum specimen. Also, the comparison between the experimental and theoretical data was made.

Finally, the output ion beam current from the ion source is used in some applications, especially for PM-355 polymer specimens. When the exposure time of the ion beam increases, the absorbance increases and the cross linking occurs.
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1.1- Introduction

An ion source is defined as a device in which the gas ions are produced, focused Giannuzzi et al [1], accelerated and emitted as a narrow intense beam Molokovsky et al [2]. The ion source is the important element in an ion beam system. In all types of ion sources Wolf [3], the ions are produced by an electrical discharge Lieberman et al [4] through a gas or vapor of liquid or solid at low pressure. The ionization is produced by electron impact in gaseous discharge. The general requirements are a source of electrons, a small region of relatively high gas pressure ($10^{-2} – 10^{-4}$ mmHg), an electric field to accelerate the electrons in order to produce intense gas discharge, plasma, with relatively high electrons and ions density and special mechanism for extracting a collimated parallel high current ion beam. The emerging ion beam from any ion source Brown [5] is divergent due to the aperture effect.

However, some emergent ions while going through the aperture hit its sides and are then lost causing the reduction of the ion source efficiency. The divergence in the ion beam is undesirable in many applications because it forces the user to place the specimen very close to the source. In particle accelerator Hellborg [6] applications, it is necessary to use an ion beam with low divergence angle. Nowadays, these apparatuses are necessary tools in scientific research, therapy, technical analyses and in a number of industrial fields. Also, they are used in surface cleaning and pretreatment for large area deposition, thin-film deposition, deposition of thick
Diamond-like carbon (DLC) films, and surface roughening of polymers for improved adhesion and/or biocompatibility [7].

Ion rays were first observed by Goldstein [8] while studying gas discharge at low gas pressure. Wien investigated the properties of the ion rays and concluded that the ion beam originated from the atoms of the gas in the discharge tube. Wien [9]. Thomson [10, 11] had been succeeded in the isotopes structure of Ne$^{20}$ and Ne$^{22}$ ion beam by using long tube for time of flight mass characteristics. The aim of the development of ion sources utilizing gas discharge was the generation of high ion concentrations by the use of relatively low applied voltage. A potential source of this type seemed to be arc discharge with a high intensity current at low voltage.

Polymer science was born in the great industrial laboratories of the world of the need to make and understand new kinds of plastics, rubber, adhesives, fibers, and coatings. Only much later did polymer science come to academic life. Perhaps because of its origins, polymer science tends to be more interdisciplinary than most sciences, combining chemistry, chemical engineering, materials, and other fields as well. Spetling [12].

In this work, a new shape of cold cathode Penning ion source is used. The electrical discharge parameters such as discharge voltage, discharge current, and output ion beam current were measured at different dimensions and different pressures using Argon gas. The effect of magnetic field on this ion source has been determined at different pressures using Argon gas. The different anode –
permanent magnet distances and magnetic field strengths are determined at different pressures using Argon gas. The effect of negative voltage applied to Faraday cup on the output ion beam current is measured at the optimum conditions of this ion source and different discharge current using Argon gas.

The simple energy analyzer consists of two grids is used. The effect of positive voltage applied to the retarding grid on the extracted ion beam current is determined at two variable values of discharge voltage and certain pressure using Argon gas.

The efficiency of the new shape of cold cathode Penning ion source is determined at constant discharge voltage equals 3.92 KV and optimum operating parameters using Nitrogen and Argon gases. The divergence angle of the ion beam exit from the emission disc is calculated. The effect of ion beam using the new shape of cold cathode Penning ion source on the optical properties of PM- 355 polymer is measured.

1.2- Classification of ion sources

An ion source can determine the characteristics of accelerated beams and is characterized by two fundamental functions:

1- The creation of intense plasma with high electron and ion densities.
2- The extraction from the plasma and focusing of the ion beam into an exit canal.
Ion sources can be classified into different categories depending on:

1- The produced amount of beam current; a low or a high ion beam.
2- The charge of beam particles; positive or negative, singly charged or multiply charged ions or even a neutral beam.
3- The method used to produce ion beams in an ion source.

1.2.1- Electron bombardment ion sources

**History**

Electron bombardment ion sources have been investigated by many people starting with **Dempster** in 1916 [13].

**Working principle**

Electrons are emitted by a cathode, usually by thermionic emission, and accelerated to an anode. Some of these primary electrons have collisions with gas atoms and ionize them. Secondary electrons from these collisions can be accelerated toward the anode to energies depending on the potential distribution and the starting point of the electron. The ionizing electrons energy is uniform and the energy spread of the ions is small. This is called the forced electron beam induced arc discharge (FEBIAD) mode see figure (1).

Ions can be extracted through the anode or through the cathode area. An additional small magnetic field confines the electrons inside the anode, lets them spiral along its lines, and increases the ionization efficiency of the ion source.
**Advantages**

Low energy spread of the ions, easy and cheap design possible.

**Disadvantages**

Low ion current, filament problems with Oxygen and corrosive elements.

**1.2.2- Magnetron ion sources**

**History**

It was first presented by Van Voorhis et al [15].

**Working principle**

The magnetron has a hollow anode, but the cathode is a straight wire parallel to the anode axis and the magnetic field which is 0.1 T or more see figure (2).
The primary electrons have to spiral along the magnetic field lines, which gives them a good ionization efficiency. Its performance is similar to a hot cathode penning source.

**Applications**

Mass separator, ion implantation, accelerators, ion beam analysis, and optical spectroscopy.

**1.2.3- Freeman ion sources**

**History**

A similar ion source design to that of the magnetron was developed at Harwell by Freeman in 1963 [16]. Optimization of the Freeman ion source for high current was done by Aitken in the 1980s [17].
Working principle and description of the discharge

It differs from the magnetron that it uses just a low external magnetic field of about 100 Gauss shown in figure (3). The magnetic field is maintained parallel to the axis of the cathode. The lifetime of this source is limited by the lifetime of the filament cathode. To improve the cathode lifetime, changing the polarity of the filament after some time of operation or heating by a.c. The Freeman ion sources are especially designed to deliver ion beams from nongaseous materials.

![Fig. (3) Freeman ion source.](image)

Advantages

High beam quality, stable operation for all elements.

Disadvantage

Cathode lifetime limited for Oxygen and corrosive gases.
Applications

It is one of the most appropriate for use in ion implanters and isotope separation till now. It is capable of delivering stable and high ion beams current for a variety of elements, gases, liquids and solids. Also it can be used for research in physics, industrial applications, and technology of ion beam generation and extraction.

1.2.4- RF ion sources

History

The first radio frequency (RF) source was built by Getting and the technology advanced by Thoneman et al and Moak et al. A review of RF ion source and their operating characteristics which produces ion-beam current more than 100 mA of axial extraction type was developed by Tallgren [18] at CERN.

Working principle and description of the discharge

In practice, an RF discharge is formed in a vacuum vessel filled with a gas at a pressure of about $10^{-3}$ to $10^{-2}$ torr. To establish a suitable discharge, a few hundred watts of RF power is required. The RF frequency can vary from a mega-hertz to tens of megahertz. A low-pressure gas can be excited by RF voltages using two ways:

(1) Capacitively coupled discharge in which a discharge between two parallel plates across which is applied an alternating potential.
(2) Inductively coupled discharge in which a discharge generated by an induction coil. Most RF ion sources are operated with the second type of discharge.

Figure (4) shows a schematic diagram of a Thonemann type inductively coupled RF ion source [19]. It consists of a quartz discharge chamber to reduce recombination at the inside surface of the vessel surrounded by the RF induction coil from the outside. There are four external variables that affect the character of the discharge and the resulting ion beam such as; the gas pressure in the chamber, the magnitude and coupling to the plasma of the RF field, the external magnetic field and the extraction voltage.

![Inductively coupled RF ion source](image)

**Fig. (4) Inductively coupled RF ion source.**

**Advantages**

Its clean resulting from absence of metallic surfaces in the discharge, high proton percentages (up to 90%), operation at low pressure yields a higher efficiency with respect to gas consumption and simplicity of construction and maintenance.
Applications

Research: for cyclotrons or synchrotrons and in neutral beam injectors for fusion research.

Industry: for ion implantation, ion beam etching, ion beam lithography, material surface modification.

1.2.5- Vacuum arc ion sources

History

The first reliable metal vapor vacuum arc (MEVVA) ion source was developed at Berkeley by Brown in the early 1980s Brown et al [20], MacGill et al [21].

Working principle and description of the discharge

The metal vapor vacuum arc occurs between hot cathode spots and a cold anode in vacuum. The principal arrangement of the vacuum arc ion source electrodes and the electric circuitry see figure (5). After ignition by a high voltage spark the vacuum arc plasma is maintained between cathode spots and the anode. The arc plasma expands through a hole in the anode into an expansion area that is usually connected to the anode via a resistor. The expansion area is terminated by an extractor grid for ion beam extraction. The ion current yield during the lifetime of a cathode is nearly constant and varies little from one cathode to the next.
1.2.6- Large area ion sources

**History**

Large area, multiple aperture ion sources were first developed as ion thrusters for space exploration Brewer [22] and Kaufman [23].

**Working principle and description of the discharge**

In order to form large ion beams, a sizable ion source chamber is needed. To achieve long cathode lifetime, the big multicusp sources are normally equipped with large numbers of Tungsten filaments. Electrons are emitted from these filament cathodes thermally. They can ionize the background gas particles and form a discharge plasma. The loss rate for the energetic primary electrons on the chamber walls (the anode) are drastically reduced by installing rows of permanent magnets on the external surface of the chamber as shown in figure (6).
The magnetic cusp-fields are localized near the chamber wall leaving the interior volume almost free of magnetic field. It has been demonstrated that if a magnetic filter field is present in the source Ehlers et al [24]. The primary electrons are prevented from reaching the extraction region.

1.2.7- surface and thermal ionization ion sources

1.2.7.1- Surface ionization ion sources

History

Ionization at hot surfaces was first investigated by Langmuir et al in 1923 [25].

Working principle

Surface ionization ion sources consist of a high temperature ionizer made of high work function material such as Tungsten, Rhenium, Iridium, or Zeolite for positive ion production, or low work function material such as Platinium coated with C, Tungsten
with a Cs monolayer, or Lanthanum hexaboride for the generation of negative ions as shown in figure (7).

![Surface ionization ion source diagram](image)

**Fig. (7) Surface ionization ion source Daley [26].**

An example of surface ionization ion sources is the source of Daley as shown in figure (7) keeps the reservoir with the liquid material separate from the porous Tungsten ionizer and, thus, only vapor can reach the ionizer, which is protected from clogging liquid. The ionizer can be made of porous material where the element to be ionized can diffuse through from the rear side (see figure 7) or can be contained inside a W- sponge **Heinz** [27]. The ionizer can be coated with material containing the element to be ionized or vapor of the respective element is directed to the hot surface where it may be ionized and reflected, adsorbed at the surface, and re-evaporated as ion or atom or just reflected as atom.

**Advantages**

Stable surface for ion extraction, suited for usually difficult elements such as halogens and alkalines, highly element selective.
Disadvantages

Extensive heat dissipation to the environment only suited for low work function or high electron affinity elements.

1.2.7.2- Thermo ionization ion sources

History

This ion source was developed around 1970 by Johnson et al at LBL [28] and by Beyer et al at JINR [29].

Working principle

Thermo ionization is the same as surface ionization but is used in connection with a hot cavity as ionizer. The ionization efficiency can be improved since the particles are trapped inside the cavity and undergo several collisions with the cavity walls before leaving the source. At low plasma densities in the source, the degree of the ionization in the volume exceeds by far the one at the surface, but stays below the theoretical limit given by using Saha equation:

\[
\frac{n_i}{n_i + n_o} = \left(1 + \frac{g_o e^{(\phi_i - \phi_g) / kT}}{g_i}ight)^{-1} \quad (1.1)
\]

Where \(n_i\) and \(n_o\) are the number of ions or atoms evaporated from the surface, \(g_i\) and \(g_o\) are the statistical weights for ions or atoms, \(\phi_i\) is the ionization potential of the atom, and \(\phi_g\) is the work function of the surface.
1.2.8- Negative ion sources

**History**

Negative ion sources have been developed according to requirements from their application fields such as accelerators, fusion research, and material science. Light negative ions, especially hydrogen negative ions, were required for high energy accelerators and fusion research. During the development of hydrogen negative ion sources, a new mechanism in hydrogen negative ion production, i.e., volume production, and then the development of hydrogen negative ion sources based on the volume production started. Heavy negative ions were required for tandem accelerators. Sputter type heavy negative ion sources were successfully developed and have recently been able to deliver sufficient negative ion currents for material science applications. Also, negative ions could be produced by means of charge transfer from a positive ion beam.

**Mechanism of negative ion production**

In an ordinary ion source plasma, an ionization cross section for negative ions by particle collision is several orders of magnitude lower than that for positive ions. An electron detachment of negative ions due to a collision with plasma electrons takes place because the absolute value of electron affinity is as low as about 1 eV. The percentage of the negative ions is quite low, and high current negative ion extraction from the plasma is considered extremely difficult.
1.2.9- Penning ion sources

History

Penning ion sources were first used as internal sources in cyclotrons Livingston [30]. Later, they were adjusted to linear accelerators as ion sources for multiply charged ions Gavin [31], and Wolf [32].

Working principle and description of the discharge

Figures (8) and (9) show the Penning ion source which consists of a hollow anode cylinder with one cathode on each end. A strong axial magnetic field confines the electrons inside the anode and keeps them oscillating between the cathodes which gives a high ionization efficiency. The cathodes can be cold or hot as shown in figure (8), one filament and a cold anticathode as shown in figure (9).

Fig. (8) Penning ion source with cold cathodes.
Gas is fed to the discharge through the anode close to the cathode(s) to ease the ignition of the arc and to keep the neutral gas flow through the extraction slit in the anode low. PIG sources can be operated in d.c. or pulsed mode, depending on the operational mode of the accelerator and on the power level needed to generate a specific ion beam. The arc voltage of a PIG ion source can vary from a few hundred volts to several kilovolts and the arc current from some mill amperes to tens of amperes, depending on the cathode and on the gas pressure. The magnetic field is between 0.1 and 1 T and is usually homogeneous.

The ion sources Rovey et al [33] on the basis of a gas discharge with oscillating electrons (Penning discharge) are widely used due to a low working pressure, high gas profitability, capabilities of ion beams formation with a large current magnitude. A Penning ion generator (PIG) works with cold or heated cathodes Brown [34] to establish a high voltage, low pressure plasma discharge Liberman et
In a typical configuration, electrons oscillate between two cathode electrodes inside an anode ring. An axial magnetic field increases the path length of ionizing electrons, making plasma production more efficient. Ions can be extracted Abdelrahman et al [35] and Giannuzzi et al [1] from PIG ion sources either axially through one cathode in the direction parallel to the discharge axis or, more commonly, radially through a slit in the anode normal to the discharge axis direction. The axial extraction is preferably applied in low intense ion sources, while the radial extraction is chosen mostly for high intensity ion sources. The Penning (PIG) ion sources have been widely used in particle accelerators Hellborg [6], sputtering Baragiola [36] and Behrisch et al [37], ion implantation Nastasi et al [38], evaporation of surfaces, electromagnetic separation of isotopes, fusion applications Loeb [39], and other ion beam equipment.

**Advantages**

High currents of multiple charged ions (Xe$^{+16}$), easy metal ion production by sputtering, internal source for cyclotrons.

**Disadvantages**

Noisy beam, medium beam quality changes during source operation time, short lifetime (filament) with highly heavy ions, expensive if separate ion source magnet is needed.
**Applications**

Internal ion source for cyclotrons, linear accelerators and can be used for high-energy ion implantation.

**1.2.10- Radial cold cathode ion source**

This ion source is designed and constructed in Accelerators and Ion Sources Department – Nuclear Research Centre – Egyptian Atomic Energy Authority and used in all experimental results for my master work [40]. A schematic diagram of the radial cold cathode ion source is shown in figure (10).

![Schematic diagram of a radial cold cathode ion source.](image)

It consists of two Copper disc anodes are placed on both sides of the Copper disc cathode at the same distance. The two Copper disc anodes and the Copper disc cathode are immersed in an insulator cylinder of Perspex material. The collector (Faraday cup) is situated
at a distance of 5 cm from the ion exit aperture of the cathode. The working gas is admitted to the ion source through a hole in the Perspex cylinder.

The operating principle of this ion source is based on the ionization produced by primary electrons colliding with gas molecules and the balance of ions in the centre between the two anodes due to equal positive voltage applied to the two anodes. Therefore high ion beam current can be extracted radially in a direction transverse to the discharge region.

**Applications:**

(1) It has been used for improving the mechanical properties such as hardness and tensile strength of stainless steel specimen with thickness 0.5 mm using pure Nitrogen gas. It was concluded that the hardness and the tensile strength of stainless steel specimen are increased about 23.25 % after exposure to pure Nitrogen ions for 200 minutes.

(2) It is used to determine the rate of sputtering of ceramic and stainless steel specimens of thickness 0.5 mm using Nitrogen gas for 90 and 200 minutes. It was found that the rate of sputtering of these specimens reach about 0.05 and 0.11 cm/sec respectively.
2.1- Ion beam formation

The extracted current from a charged particle source is limited either by the emission capability or by space charge forces. The maximum current density \( J \) can be calculated by the Child-Langmuir [41, 42] equations (2.1), (2.2):

\[
J (A/m^2) = \frac{4 \varepsilon_0}{9} \sqrt{\frac{2q}{m}} \cdot \frac{\Phi^{3/2}}{d^2} \quad (2.1)
\]

With permittivity \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \), electric charge \( q = q^* \times 1.602 \times 10^{-19} \text{ AS} \), \( q^* \) is the charge state, atomic mass \( m = u \times 10^{-24} \text{ g} \), \( u \) is the mass in atomic mass units, \( \Phi (\text{V}) \) is the potential drop across the gap \( d \text{ (m)} \), in more practical units:

\[
J (A/m^2) = \sqrt{\frac{q^*}{u}} \cdot \frac{\Phi (\text{KV})^{3/2}}{d (\text{mm})^2} \quad (2.2)
\]

For beam transport, not only the extracted current, but also the beam quality is important. The beam quality is measured by the emittance, which describes the particle distribution \( \delta \) in phase space \( \delta \). A measure of the density of the four dimensional phase space density is the brightness \( B \) of a beam and can be calculated by the relation:

\[
B \left[ A/ (\text{m}. \text{ rad})^2 \right] = \frac{I(A)}{\pi^2 \cdot \varepsilon_x (\text{m}.\text{rad}) \cdot \varepsilon_y (\text{m}.\text{rad})} \quad (2.3)
\]
The brightness is a measure of the current density per unit solid angle. When the beam is accelerated, the transverse phase space will shrink with the velocity.

The normalized emittance is therefore:

\[ \epsilon_{n, x} = \epsilon_x \cdot \beta^* \]  
\[ \epsilon_{n, y} = \epsilon_y \cdot \beta^* \]

(2.4) \hspace{1cm} (2.5)

2.1.1- Extraction from fixed emitters

The particle starting coordinates are given by the geometry of the emitter itself. The emittance of the beam is determined by the emitting area, its shape, and the temperature of the emitted particles. The longitudinal emittance is given by the temperature of the particles and the stability of the extraction voltage.

2.1.2- Extraction from plasma sources

In plasma sources the ions are generated in a discharge chamber. From the point of generation they drift until a fraction of them reaches the extraction region. The saturation value of ion current density, \( j_s \), which can be extracted from plasma, is given by Coupland et al [43] and Thompson [44]:

\[ \left[ \frac{A}{m^2} \right] = n_i \cdot q \cdot \sqrt{\frac{kT_e}{m}} \]  

(2.6)

Where \( k = 8.616 \times 10^{-5} \) eV/ K, which is the Boltzmann constant, \( T_e \) is the electron temperature, and \( n_i \) is the ion density in the plasma.
The emittance of the extracted beam is given by the plasma parameter, existing magnetic fields, and aberrations in the extraction. There is only one potential for a given geometry and plasma conditions that will create a beam with desired properties. The Poissance $\Pi$ Green [45] and Lejeune [46] has been defined as an electrical quantity:

$$\Pi = \frac{I}{\varphi^{3/2}}$$  \hspace{1cm} (2.7)

With $I$ the extracted current, the perveance $P_c$ has been defined as a geometric quantity Green [45] and Lejeune [46]:

$$P_c = \frac{4eO}{9} \sqrt{\frac{2q}{m}} \cdot \frac{A}{d^2}$$  \hspace{1cm} (2.8)

Where $A$ is the emitting area.

The minimum theoretical divergence angle $\omega_o$ of the beam for planar extraction systems (slit) has been estimated as Thompson [44] and Green [45]:

$$\omega_o = 1.41 \cdot \frac{a}{d} \cdot \left| 1 - \frac{1.47 \Pi}{P_c} \right|$$  \hspace{1cm} (2.9)

Where $a$ (m) is the half width of the slit and $d$ (m) is the gap width. For round apertures with radius $r$ a similar expression can be estimated:

$$\omega_o = 0.5 \cdot \frac{r}{d} \cdot \left| 1 - \frac{1.67 \Pi}{P_c} \right|$$  \hspace{1cm} (2.10)
According to these equations round apertures have smaller divergence angles; however, zero divergence can not be achieved because of:

- Thermal energy spread in the plasma
- Aberrations within the extractor

For the cylindrically symmetric case the maximum current can be estimated and the assumption of a certain aspect ratio. A good aspect ratio is on the order of $S \sim 0.5$ Green [45].

$$I \text{ (mA)} = 0.703 \sqrt{\frac{q^2}{u}} \cdot \varphi \text{ (KV)}^{3/2} \quad (2.11)$$

The voltage breakdown limit determines the necessary gap width. The empirically determined limit is:

$$d \text{ (mm)} \geq 1.41 \times 10^{-2} \cdot \varphi \text{(KV)}^{3/2} \quad (2.12)$$

The emittance of the extracted beam can be estimated as:

$$\varepsilon_{x,y} \sim \omega_0 \cdot r_{opt} \quad (2.13)$$

If the emittance has a waist at that location, $\omega_0$ is the maximum divergence angle. The expected emittance can be rewritten as:

$$\varepsilon_{x,y} \geq 0.7 \times 10^{-2} \cdot \omega_0 \cdot \varphi \text{ (KV)}^{3/2} \quad (2.14)$$

The upper limit of the brightness can be given as:

$$B \ll 1.5 \times 10^3 \sqrt{\frac{q^2}{u}} \frac{1}{\omega_0^2 \cdot \varphi^{3/2}} \quad (2.15)$$
2.2- Extraction of ions from plasma

The extraction process basically consists of applying a high voltage between an ion reservoir and a perforated accelerated electrode. The trajectories of the accelerated ions, which immediately determine the maximum beam quality are influenced by several factors: The applied field strength, The shape of the emitting surface which may be solid (field- and surface ionization sources) or flexiable (plasma sources), and The space charge density of the resulting beam itself. In the case of plasma sources, the emitting surface is termed by the "meniscus". Its detailed shape depends on the electrical field distribution due to the applied boundary conditions and the local densities of plasma ions, electrons and accelerated ions.

With plasma sources, the plasma meniscus acts as the boundary layer between the discharge plasma and the accelerated beam particles. The depth and position of this layer, with respect to the surrounding electrodes depends on the densities of plasma electrons and ions, their mobilities which can be expressed in terms of temperatures. From ion optical considerations one can deduce that the ion temperature for some sources might typically be around 0.2eV, whereas a typically electron energy would be a few electron volts Ehlers et al [47].
2.2.1- Design of the ion extraction system

In order to extract ions from the appropriate source, and to accelerate and collimate them for subsequent focusing into the desired being shape, an arrangement of carefully designed electrodes must be used. This electrode system must create the proper configuration of electric fields at the surface of the ion source and along the acceleration path. The surface which forms the source of ions can be either of fixed geometrical form. An optimum geometry for the extraction electrode is essential, with the following requirements:

(a) It must give high convergent ion beam free of aberration with maximum number of ions.
(b) It must prevent neutral particles from leaking to the high-vacuum chamber.

If these two requirements are satisfied, the efficiency of the ion source is increased.

2.2.2- Classical extraction system

The plasma is an equipotential region with very weak electric field i.e. no electric field inside. If an electrode surface comes nearer to the plasma surface $S_1$, figure (1-a), with potential less than that of the plasma surface, a positive ion sheath is formed and the whole potential difference between the plasma and this electrode is localized within the sheath, the wall of the discharge vessel or any electrode carrying a potential less than that of the plasma. As the
potential difference between the plasma and the electrode $S_2$ Changes, the thickness of the sheath alters in such a way that the surface $S_1$ remains in equilibrium, where $S_1$ is an equipotential surface, $v_{s1} = v_p$, where $v_p$ is the plasma potential.

When a hole is drilled in $S_2$ (the sheath) the plasma expands and gives a concave plasma boundary outside the discharge as shown in figure (1-b) Thonemann et al [19]. This plasma boundary is the ion-emitting surface and ions can be extracted from it, or diffused out, by applying a negative potential to an electrode $S_3$, (extractor), nearest to it, as shown in figure (1-c). The plasma boundary is considered as an elastic electrode, its shape and position is affected by the electric field, the extractor electrode, the shape of this electrode, and the discharge parameters.

To obtain a parallel ion beam from the plasma boundary surface an optimum potential is applied between the shield and the extraction electrode, see figure (1-c). At that potential difference the emitting surface of the plasma boundary is flat. After an intense beam has passed the extraction electrode, its space charge has to be compensated; otherwise servers below-up of the beam envelope would occur. In many cases some of the residual gas particles that are present within the beam line will be ionized by impinging beam ions, and this process can generate a sufficient number of compensating electrons.
Fig.(1) Schematic Diagram of ion beam formation AWAD [48].

But the electrons must be kept from being accelerated back into the source by the extraction field. When a high ion current is required, the aperture hole in the extraction electrode can be increased, also higher extraction voltages may be used to form a concave plasma boundary which results in producing a focused beam of higher intensity as shown in figure (2-a). However, increasing the area of the holes cannot be done indefinitely because of gas loading, and the use of high extraction voltages which may be accompanied by high voltage breakdown.
Therefore, the advantages of plasma diffusing outside the source through a small aperture, which restricts the gas flow from the source to the extraction region, can be used. This depends upon the plasma penetration through a small hole outside the source. This principle is well known and was first used in ion sources by Gabovich et al [49]. The plasma passes through a small aperture to the extraction region and leads to bigger plasma boundary which results in a larger ion current. The ions can be extracted from the expanded plasma by applying a negative potential electrode S3 as shown in figure (2-b). This electrode may be a cylinder or a grid Solpnshkov [50]. This method has the advantage of producing ion beams with low divergent angle Collins et al [51]. Another way for ion extraction is shown in figure (2-c). It depends on fixing a grid in the hole of S2 electrode and using an extraction grid. This gives well-defined extraction geometry and the plasma boundary in this case will be defined according to the geometrical design Rose [52]. These two conditions are satisfied for an emissive conducting surface, operating in space-charge-limited conditions; S is an equipotential surface, with zero normal gradient. Gas discharge ion sources that provide beams of high intensity fall into two categories:

(1) The density $n_i^+$ is low or medium ($10^8 < n_i^+ < 10^{10}$ cm$^{-3}$).
(2) The density $n_i^+$ is very high ($10^{10} < n_i^+ < 10^{14}$ cm$^{-3}$); the method of producing the plasma determines the category.
2.2.3- Different shapes of extraction system

**a- Axial diode system**

This simple extraction scheme can be applied if space charge compensation within the extracted ion beam is not important. Two electrodes determine the extraction system: an outlet electrode and a ground electrode.

**b- Axial Triode system**

The extraction system consists of three electrodes: an outlet electrode, a screening electrode, and a ground electrode. The reasons for using a triode extraction system:
- Preserving the space charge compensation of the extracted ion beam (accel-decel system).
- Having the possibility to change the extraction field strength without changing the beam strength

Tinschert et al [53] and Spädtke et al [54].

**c- Multigap Extraction Systems**

Extraction systems with more electrodes such as tetrodes Whealton [55] or pentodes Keller et al [56] have been used for special purposes. Possible applications are special beam forming electrodes to improve the beam quality, post acceleration to higher voltages, or intermediate electrodes in H⁻ extraction systems to separate the electrons from the negative ions.

**d- Multiaperture Extraction System**

If the emitting area is too small to deliver enough current, it can not be increased above a certain limit without reduction in beam quality. One possible solution to this problem is to increase the number of extraction holes. In practice, up to several thousand holes have been realized. The emitting area of the multiaperture system is in such a case. The highest achievable transparency can be estimated as ~ 60%.
**e- Mesh Extraction System**

Advantages of mesh extraction systems are:

- It provides a stable, well defined emitting surface.
- Emission control capability True [57].
- High transparency.

The disadvantage is the limited lifetime of the mesh due to sputtering. A mesh in front of the extraction system can also be used to minimize the noise of the beam Arango et al [58] and Hiraoka et al [59].

**f- Postacceleration**

If the extraction voltage is not high enough for the desired beam energy, the post acceleration is necessary. This requires that the charged particle source, including all power supplies, be installed on a high voltage platform which the beam can be post accelerated. Mass and charge state can be done on the high voltage platform.

The post acceleration can be done with a multi- or a single-gap acceleration column. In both cases the focusing strength of the gap should be matched to the beam emittance, the rigidity of the beam, and the defocusing strength of the space charge. Multigap structures normally have low focusing power, best suited for lower ion currents. For higher beam
current, stronger focusing single-gap devices are used. A negative screening electrode can be used behind the acceleration system to preserve the space charge compensation of the accelerated beam.

**g- Extraction in Transverse Magnetic Fields**

When the magnetic field is perpendicular to the extraction system, charge separation takes place already in the extraction. An example of such a situation is the radial extraction from a Penning ion source.

### 2.3- PIG ionization

Penning ionization is a form of chemi-ionization, an ionization process involving reactions between neutral atoms and/or molecules. Arango et al [58] and Hiraoka et al [59]. The process is named after the Dutch physicist Frans Michel Penning who first reported it in 1927 Penning [60].

Penning ionization refers to the interaction between a gas-phase excited-state atom or molecule $G^*$ and a target molecule $M$ resulting in the formation of a radical molecular cation $M^{+\cdot}$, an electron $e^-$, and a neutral gas molecule $G$ [61]:

$$G^* + M \rightarrow M^{+\cdot} + e^- + G \quad (2.16)$$

Penning ionization occurs when the target molecule has an ionization potential lower than the internal energy of the excited-
state atom or molecule. Associative Penning ionization can also occur:

$$G^* + M \rightarrow MG^{+\bullet} + e^-$$  \hspace{1cm} (2.17)

Surface Penning ionization refers to the interaction of the excited-state gas with a surface S, resulting in the release of an electron.

$$G^* + S \rightarrow G + S + e^-$$  \hspace{1cm} (2.18)

The positive charge symbol $S^+$ that would appear to be required for charge conservation is omitted, because S is a macroscopic surface and the loss of one electron has a negligible effect.

2.4- Effect of static magnetic field on gas discharges

The electron and ion currents leaving the plasma of the discharge are determined by diffusion. If the gas discharge is exposed to a static magnetic field, the diffusion of charged particles will change. If a d.c. gas discharge is exposed to a magnetic field with a direction parallel to that of the electric field, the charged particle currents will decrease towards the tube wall in the direction normal to the magnetic field. This decrease is caused partly by the change in the movement of electrons normal to the axis under the magnetic field action. As the magnetic field increases, smaller number of electrons is able to reach the tube wall as they move on a helical path with decreasing radius. The other cause of the decrease is understood
from the diffusion theory since in the equation describing the electron current reaching the wall by diffusion as:

\[ J_e = - D_e \text{grad } n_e \]  

(2.19)

The diffusion coefficient \( D_e \) decrease in a magnetic field in the direction normal to that of the field according to the ratio:

\[ D_H \sim \frac{D_{H=0}}{H^2} \]  

(2.20)

As given by:

\[ D_H = \frac{D_{H=0}}{[1 + (x^2 H^2 / v_x^2)]} \]  

(2.21)

The value of the diffusion coefficient remains unchanged in the direction parallel to that of the magnetic field. Because of the greater mass of the ions, their motion is only slightly affected by the magnetic field. If the discharge is exposed on a magnetic field, two effects will assert themselves. One of these effects causes the positive column of the discharge to be deflected by the magnetic field towards one of the tube walls. The other effect is the decrease in the diffusion of charged particles in the direction normal to the magnetic field, which in this case coincides with the directions of the axes of the electric field and the discharge.

In the high frequency discharge with alternating electric field the charged particle current from the quasi-neutral plasma is determined by the diffusion process. The exposure of an alternating magnetic field induced high frequency discharge to a static magnetic field is also responsible for effects other than the resonance phenomenon. If
the value of the magnetic field continues to increase, it causes the power consumption and the plasma concentration to increase as well. This phenomenon can be explained by the mentioned decreasing diffusion in the direction normal to the magnetic field.

2.5- Cold cathode arc- discharge ion sources with oscillating electrons in magnetic field

In the ion sources with heated cathode, the cathode lifetime limits that of the ion source and the construction of the assembly is complicated by the use of heated cathode. Many investigations prefer cold cathode ion sources for the production of both low and high intensity ion beams. The latter have a longer lifetime, they are of simpler design and their power requirement is lower. These types are known as cold cathode, Penning type ion sources Nagy [62, 63].

The cathode lifetime, the anode voltage and the discharge stability must also be considered. The cathode lifetime is determined by the degree of cathode sputtering while the anode voltage and the stability of the discharge depend on the maintenance of the cathode surface properties. The ions are extracted from the cold cathode, Penning type ion sources either axially in the direction parallel to that of the discharge axis and of the magnetic field, or transversally in the direction normal to the axial direction. The axial extraction is applied in low intensity ion sources, while the transversal arrangement is chosen for high intensity ion sources. Low intensity beams can be extracted with a transversal and high intensity beams
with an axial arrangement. The contribution from atomic ions to the beams extracted from these types of ion source is rather small, not more than 10 to 50 per cent of the beam.

2.5.1- Cold cathode Penning type ion sources with axial ion extraction

One of the Penning type ion sources with axial ion extraction which produces low intensity beams utilizing a permanent magnet for the generation of the magnetic field as shown in figure (3) Nagy [64].

![Diagram of a low intensity ion source with cold cathode, oscillating electrons and axial ion extraction.](image)

Fig. (3) Keller's version of a low intensity ion source with cold cathode, oscillating electrons and axial ion extraction.

The cathodes of the ion source are hollow to improve the stability of the discharge. Cathodes of this type are made of iron Keller [65] or magnesium Keller [66, 67]. In this source they are attached to the mild iron poles of the permanent magnet. The ions are extracted
from the discharge volume at the anticathode aperture. This ion source operates with iron cathodes in the anode voltage range \( U_a = 470 \) to \( 520 \) V and the discharge current is in the range \( I_a = 10 \) to \( 120 \) mA. The ion current obtainable from this source varies from \( 0.1 \) to \( 1 \) mA. The magnetic field applied to the discharge volume of this source is \( \sim 1000 \) gauss.

2.5.2- Cold cathode Penning type ion sources with transversal ion extraction

One of the Penning type ion sources with axial ion extraction which produces low intensity beams can be seen in figure (4).

![Image of ion source](image)

Fig. (4) Heiniche – Bethge – Bauman's low intensity ion source with cold cathode, oscillating electrons and transversal ion extraction.

The source has 3 mm thick cathodes made of Tantalum and attached to the poles of the electromagnet. The cathodes are
electrically isolated from the magnetic poles. Their useful lifetime is about 12 hours. The outlet aperture is on the side wall of the cylindrical Molybdenum anode. The anode is attached to the electrode of the extracting system and it can be adjusted along with the latter. The magnetic field in the discharge volume varies between 0.5 and 1 k gauss.

The maximum ion current obtainable from this source is ~ 100 µA. In the high intensity ion source the cold cathodes are exposed to intense ion bombardment. The temperature of the cathode surfaces can be raised by this bombardment which causes the electron emission to increase together with the intensity of the discharge. This effect can become more important if the heat conduction of the cathodes is poor. In this case, the voltage drop in the discharge decreases to a few hundred volts Mills et al [68].

2.6- Paschen's law

Friedrich Paschen developed a law in 1889 Paschen [69], which sets the breakdown voltage as a function of the product of the pressure (p) and the inter-electrode distance (d):

\[ V_b = f (p \times d) \]  

(2.22)

Townsend [70] presented a model for the gas breakdown process in 1915. From this model, it is possible to deduce mathematical formulae for the Paschen coefficients. Paschen’s law states that the breakdown potential, \( V_b \), of a gas is a function of the pressure
multiplied by the distance between the electrodes. There will generally be a minimum value for $V_b$ and that value is constant for a given electrode pair in a given gas. The $V_b$ versus PD curve is found by applying a voltage across two electrodes in a vacuum chamber. The voltage is increased until current crosses the gap. The pressure is then adjusted and the process is repeated [71].

$$V_{\text{max}} = \frac{A \, p \, d}{\ln (p \, d) + B}$$  \hspace{1cm} (2.23)

$$A = \frac{V_i}{1.013 \times 10^5 \text{ Pa} \, l_o}$$

$$B = -\ln \left( 1.013 \times 10^5 \text{ Pa} \, l_o \ln \left( 1 + \frac{1}{\gamma} \right) \right)$$  \hspace{1cm} (2.24)

The first Townsend coefficient $\alpha$ is the probability to ionize a gas neutral by collision per unit length of path, i.e. it is the number of collision per unit length of path times the ionization probability per collision. Hence:

$$\alpha = \frac{1}{\lambda_e} \times \exp \left( \frac{-E_i}{E_e} \right)$$  \hspace{1cm} (2.25)

With $\lambda_e$ the electrons mean free path, $E_i$ the ionization energy of the gas, $E_e$ the electron energy colliding with the gas neutral. Equation (4) is more commonly known as (Cobine [72] p. 162):

$$\alpha = A \, P \, \exp \left( -BP/E \right)$$  \hspace{1cm} (2.26)
With $E_e = e \lambda_e E$. Assuming that the electric field is uniform before the gas breakdown ($E = V_b / d$) equation (2.22) can be transformed to:

$$V_{br} = BPd / (C + \ln Pd)$$

(2.27)

With $\lambda_e = K_B T / \sigma_{ei} P$, one can deduce:

$$A = \sigma_{ei} / K T$$

(2.28)

and the Paschen coefficients:

$$B = \sigma_{ei} E_i / e K T,$$

$$C = \ln \left( \sigma_{ei} / \alpha d K T \right)$$

(2.29)

Where $\sigma_{ei}$ is the electron impact ionization cross-section (in m$^2$), $E_i$ is the ionization energy of the gas (in J), $e$ is the elementary charge (in C), $k$ is the Boltzmann constant, $T$ is the temperature (in K). The ionization cross section of Argon by electron impact has been the topic of numerous investigations and give consistent results with a maximum value (regarding its dependency on the impacting electron energy) ranging from $2.7 \times 10^{-20}$ m$^2$ [Lotz 73] to $3.8 \times 10^{-20}$ m$^2$ [Jha et al 74]. We take the value given $3.5 \times 10^{-20}$ m$^2$, this leads to the calculated value for $A$ is $8.5$ Pa$^{-1}$m$^{-1}$, which is in the range of the experimental values. Similarly, the calculated value of cold Molybdenum cathode Penning ion source for $B$ is $82.84$ V Pa$^{-1}$m$^{-1}$. 

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2.7- Particle analyzers

Ion-assisted plasma processing is an active field of research. The ion flux onto the substrate is as well as the ion energy distribution having been identified as significant parameters for dry etching or thin film deposition. External bias voltages are typically applied to the substrate to manipulate the ion energy distribution during processing Patterson et al. [75]. It has been shown that adequate biasing of the substrate can significantly support the etch selectivity in semiconductor processing Wang et al. [76], Silapunt et al. [77], Buzzi et al. [78], or the synthesis of certain crystalline phases in the deposition of hard coatings Yamada et al. [79], and Audronis et al. [80]. Several experimental and theoretical methods have been developed and applied to determine the ion flux and the ion energy distribution at the substrate, such as the use of ion mass/energy analyzers Janes et al. [81], Abraham et al. [82], Woodworth et al. [83] or extensive modeling of plasma and sheath Kratzer et al. [84], Agarwal et al. [85].

More sophisticated analyzers can be used for the analysis of the atoms, molecules or their ions as well as the electrons in the discharge. Depending on the type of analyzer, we can obtain the energy distribution, the mass distribution or both. Particle energy analyzers are more versatile, and can be used to obtain more reliable measurements of the electron and ion energy distribution functions than we can obtain from probes, at the price of complexity and
a greater perturbation of the plasma. In large volume plasma, the analyzer can be placed within the plasma Oertl et al. [86], Stenzel et al. [87], but in most laboratory plasmas used for materials treatment, a more convenient arrangement is to place it behind an electrode, coupled to the plasma via a small hole. The most obvious example is to use the analyzer to measure the velocity or charge/mass distribution of the ions (or neutral particles) incident on a substrate (for example the cathode of a discharge).

2.7.1- Energy analyzers

It is often important to measure the energy of the heavy charged particles in plasma. Although probes can provide useful and detailed information about the electron component, such measurements of the ions require the use of an energy analyzer, where the electron component can be removed by the application of suitable potentials. The energy distribution of the emergent ion beam was investigated by using a simple retarding field analyzer which is shown in figure (5). This energy analyzer was made from two Copper grids which were of 40% transmission. It consists of two grids called screen and retarding grids, in which the positive potential, \( V_R \), was applied to the retarding grid and the screen grid was at the earth potential. The purpose of the screening grid is to screen the Faraday cup from the high field produced by the retarding grid so that the secondary electrons from the Faraday cup are not accelerated towards the retarding grid.
2.7.2- Mass analyzer

In most plasma, there are several ion species present; even in relatively clean hydrogen plasma in fusion machines, there are always contaminants such as carbon which is sputtered from the walls and which enters the plasma. The measurement of these ions is important for correlation with the general level of contamination in the plasma. Although it is interesting to measure the energy distribution of these ions, it is crucial to measure their charge states and absolute concentrations (if possible). In plasmas for materials treatment, the multiple reactive species in the plasma are responsible for the phenomena which we want to promote: etching of a surface, surface deposition of a given material, or the production of new
species in plasma chemistry. When we want to measure the mass spectrum of charged particles, we need to use mass analyzers – devices which separate the ion current according to the mass of the ion.

There are several designs which have been used over the years, some with more universal applicability than others, and some with particular interest because of their compact nature. A convenient orientation is to place the analyzer in an evacuated chamber, behind the cathode of the discharge, connected via a small hole to the main discharge volume.

In this case, a small fraction of the ions streaming toward the cathode surface will pass through the hole, and be analyzed. As in the case of the energy analyzers, this hole should be smaller than the sheath dimension (a few Debye lengths) in order to be able to exclude the plasma. Since the size of the hole will then scale with $n^{-\frac{1}{2}}$, we find that the current will only depend on the electron temperature and the ion mass.
3.1- Design and construction of ion source

Many trials have been made on Penning ion source. Finally, the design and construction of the new shape Penning ion source with two cold Molybdenum cathodes is given as below with the following dimensions to suit the required parameters used in applications.

3.1.1- Design of the cold Molybdenum cathode Penning ion source

A schematic diagram of the cold Molybdenum cathode Penning ion source is shown in figure (1). It consists of Copper cylindrical hollow anode of 40 mm length, 12 mm diameter, and has two cone ends of 15 mm length, 22 mm upper diameter and 12 mm bottom diameter. The two movable Molybdenum cathodes are fixed in Perspex insulator and placed symmetrically at two ends of the anode. The Copper emission disc of 2 mm thickness and has central aperture of different diameters is placed at the middle of the anode for ion beam exit. The inner surface of the emission disc is isolated from the anode by Perspex insulator except an area of 5 mm diameter to confine the discharge in this area. Faraday cup is placed at different distances from the emission disc aperture and used to collect the output ion beam from the ion source. The Copper extractor electrode is placed at different distances from the emission electrode and used to extract the ions from the ion source.
An axial Samarium - Cobalt permanent magnet is placed around the anode at different distances to increase the ionization efficiency. The working gas is admitted to the ion source through a hole of 1 mm diameter in the outer surface of the cylinder anode.

3.1.2- Electrical circuit of the ion source

The electrical circuit of the cold Molybdenum cathode Penning ion source is shown in figure (2). Digital stabilized power supply is used for measuring the gas discharge which is capable to produce an output d.c voltage which varies from 0 to 20 KV with d.c current varying from 0 to 25 mA. A limiting resistance of 100 KΩ, 10 watt is used to protect the power supply when the breakdown occurs.
A voltmeter (kilovolts) ranging from 0 to 20 KV was connected in parallel and ammeter (milliamperes) measuring from 0 to 10 mA was connected in series with the load to measure both the discharge voltage $V_d$ and the discharge current $I_d$ of the working gas respectively.

![Electrical circuit of cold Molybdenum cathode Penning ion source.](image)

The Faraday cup terminal was connected to the earth through ammeter (microamperes) from 0 to 1000 $\mu$A ranges to measure the output ion beam current $I_b$ extracted from the ion source.

### 3.2- vacuum system characteristics

The experimental investigations have been carried out by using a high vacuum system of standard type. It consists of a stainless steel Mercury diffusion pump backed by rotary pump. A liquid Nitrogen
trap is fixed between the vacuum system and the ion source vacuum chamber. A differential solenoid – operated valve which is designed to close the vacuum manifold and to admit atmospheric air into the pump when it is stopped. Prepumping of the chamber is carried out using a vacuum manifold branch with a hand – operated valve. The components of the system used, is shown in the figure (3) which consists of:

3.2.1- rotary pump

It is Edwards type 1 Sc 450 B of speed 450 L/ minute. It is used for obtaining a pressure about $10^{-2}$ to $10^{-3}$ mmHg.

3.2.2- diffusion pump

It is speedivac Edwards with electrical heater type 6 M 3 A of speed 270 L/ sec. It is used to obtain high vacuum about $10^{-3}$- $10^{-7}$ mmHg. It must be operated continuously in series with the rotary pump. In a vacuum system, a chamber is connected directly to a diffusion pump, backed by a rotary pump.

3.2.3- liquid Nitrogen trap

The liquid Nitrogen trap is fixed between the vacuum system and the ion source vacuum chamber.
Fig. (3) Schematic diagram of the experimental arrangement.
3.2. 4- Vacuum chamber

The ion source vacuum chamber is a stainless steel cylindrical tube of diameter 25 cm and 18 cm length. The chamber has a Perspex flange carrying the terminals of the electrical circuit which are feeding and measuring the parameters governing the characteristics of the ion source at one side. The electrodes are electrically connected to the other side of the flange.

A digital vacuum meter type 1005 Edwards with two gauge heads is used, where the vacuum gauge head (pirani) is used to measure the fore vacuum inside the connecting tubes and the ion source vacuum chamber. The vacuum gauge head (ionization lamp) is used to measure the high vacuum inside the ion source vacuum chamber.

3.2.5- Gas handling of the system

The gases (Argon and Nitrogen) used in the experimental investigations are admitted into the ion source from cylinder tanks via tubes through a rubber hose connected with a needle valve to control and adjust the rate of flow of the gas used. Gas is fed to these two ion sources usually through aperture in the anode.

3.2.6- Operating of the system

The ion source has been cleaned before connected to the vacuum system. The procedure of cleaning is done by polishing to remove irregular parts from the surfaces. Then washing all electrodes,
envelope and Faraday cup with Ethanol and distilled water to remove the contamination due to the eroded material of the discharge. The rotary pump is switched on and left running until the ultimate pressure of the pump is reached and then the valve between the rotary pump and ion source chamber is opened. Then the water cooled diffusion pump is connected to the ion source chamber after the pressure in the connecting tubes and ion source chamber reaches $10^{-2}$ mmHg. The trap between the diffusion pump and the ion source chamber is filled with liquid Nitrogen, this is necessary to avoid the Mercury vapor to contaminate the ion source chamber. The experiment starts after the pressure in the ion source chamber is about $10^{-6}$ mmHg.

The gas is admitted through the needle valve to flow in the ion source to reach the working pressure which depending upon the aim of the experiment ranges between $10^{-2}$ to $10^{-4}$ mmHg. Then the instrument is ready to be used for measuring the different parameters. For a fixed geometry of the ion source and gas pressure, the anode voltage is increased gradually to reach the glow discharge region. Glow discharge sets up between the two cathodes and anode. With the increase of the anode potential, the plasma boundary layer is extended to the cathode, where the glow discharge takes place between the anode and the cathode for a potential range between 0 to 8 KV.
The ion beam is extracted from the discharge region through the exit hole placed on the anode and collected by the Faraday cup. The discharge current, the discharge voltage and the output ion beam current for various chamber pressures were measured for different gases.
4- Experimental Results of a Cold Molybdenum cathode Penning Ion Source

The experimental results have been carried out using a cold Molybdenum cathode Penning Ion Source as shown in figure (1) which has the following dimensions:

![Diagram of cold cathode Penning ion source](image)

![Diagram of cold cathode Penning ion source](image)

Fig. (1) Dimensions of cold cathode Penning ion source.

4.1- Determination of the optimum anode – cathode distance

In this experiment, the distance between the anode and each cathode, \( d_{A-C} \), is varied with values equals 5, 6, 7, and 8 mm at \( D_{em} \) equals 1.5 mm, \( D_{uncovered \ em. \ disc} \) equals 5 mm, and \( d_{em.-F.C.} \) is fixed at 3 cm. The optimum \( d_{A-C} \) for stable discharge current and a maximum output ion beam current can be obtained.
4.1.1- Input characteristics

Figures (2), (3), (4) and (5) show the discharge voltage, $V_d$ (KV), versus the discharge current, $I_d$ (mA), at different pressures using Argon gas, $D_{em} = 1.5$ mm, $d_{em \cdot F.C} = 3$ cm, and $d_{A-C}$ is varied with values equal to 5, 6, 7, and 8 mm. It is clear from the figures that the discharge current increases with increasing the discharge voltage and the discharge voltage starts at lower potential in case of high pressure ($6 \times 10^{-4}$ mmHg) than that in case of low pressure ($3 \times 10^{-4}$ mmHg).

![Graph showing discharge current versus discharge voltage](image)

Fig. (2) Discharge current versus discharge voltage at $d_{A-C} = 5$ mm, $D_{em} = 1.5$ mm and $d_{em \cdot F.C} = 3$ cm using Argon gas.
Fig.(3) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.

Fig.(4) Discharge current versus discharge voltage at $d_{A-C} = 7$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.
Fig.(5) Discharge current versus discharge voltage at $d_{A-C} = 8$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.

4.1.2- Output ion beam characteristics

Figures (6), (7), (8) and (9) show the output ion beam current, $I_b$ ($\mu$A), versus discharge voltage, $V_d$ (KV), at different pressures, $D_{em} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, and $d_{A-C}$ is varied with values equal to 5, 6, 7, and 8 mm using Argon gas. It is clear that these figures are similar in shape to the discharge voltage – discharge current curves. In order to increase the output ion beam current through the discharge; we must increase the number of electrons created by the ionization. The electric field and hence the voltage across the anode and the cathode must be large to increase the ionization rate by the electron impact.
Fig. (6) Output ion beam current versus discharge voltage at $d_{A-C} = 5$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.

Fig. (7) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.
Fig. (8) Output ion beam current versus discharge voltage at $d_{A-C} = 7$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.

Fig. (9) Output ion beam current versus discharge voltage at $d_{A-C} = 8$ mm, $D_{em.} = 1.5$ mm and $d_{em.-F.C} = 3$ cm using Argon gas.
Figures (10), (11), (12) and (13) show the output ion beam current, $I_b$ (µA), versus discharge current, $I_d$ (mA), at different pressures, $D_{em} = 1.5$ mm, $d_{em-F.C.} = 3$ cm and $d_{A-C}$ is varied with values equal to 5, 6, 7, and 8 mm using Argon gas. It is clear from the figures that the output ion beam current increases with increasing the discharge current and at $P = 3 \times 10^{-4}$ mmHg and $d_{A-C} = 6$ mm, a maximum output ion beam current equals 106 µA can be obtained.

![Graph](image)

Fig.(10) Output ion beam current versus discharge current at $d_{A-C} = 5$ mm, $D_{em} = 1.5$ mm and $d_{em-F.C.} = 3$ cm using Argon gas.
Fig. (11) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em} = 1.5$ mm and $d_{em-F.C} = 3$ cm using Argon gas.

Fig. (12) Output ion beam current versus discharge current at $d_{A-C} = 7$ mm, $D_{em} = 1.5$ mm and $d_{em-F.C} = 3$ cm using Argon gas.
4.1.3- The optimum gap distance between the anode and the cathode.

Figures (14) and (15) show the output ion beam current, \( I_b (\mu A) \), versus the anode – cathode distance, \( d_{A-C} \) (mm), at \( D_{em.} = 1.5 \) mm, \( d_{em.-F.C} = 3 \) cm, \( I_d \) equal to 1 and 2 mA respectively, and different pressures using Argon gas. It is obvious from the curves that at \( P = 3 \times 10^{-4} \) mmHg, \( I_d = 1 \) mA and \( d_{A-C} = 6 \) mm, a maximum output ion beam current equal to 61 \( \mu \)A can be obtained, but at \( I_d = 2 \) mA, a maximum output ion beam current equal to 106 \( \mu \)A can be obtained. While before and after this distance the output ion beam current decreases.
Fig. (14) Output ion beam current versus anode – cathode distance at different pressures, $D_{em.} = 1.5\ mm$, $d_{em.-F.C} = 3\ cm$, and $I_d = 1\ mA$ using Argon gas.

Fig. (15) Output ion beam current versus the anode – cathode distance at different pressures, $D_{em.} = 1.5\ mm$, $d_{em.-F.C} = 3\ cm$, and $I_d = 2\ mA$ using Argon gas.
Figures (16) shows the output ion beam current, $I_b$ ($\mu$A), versus the anode – cathode distance, $d_{A-C}$ (mm), at $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, $I_d$ equal to 1 and 2 mA, and $P= 3 \times 10^{-4}$ mmHg using Argon gas. It is obvious from the curves that at $I_d = 2$ mA, $d_{A-C} = 6$ mm, a maximum output ion beam current equal to 106 $\mu$A can be obtained. Also, at $I_d = 1$ mA, $d_{A-C} = 6$ mm, a maximum output ion beam current equal to 61 $\mu$A can be obtained. While before and after this distance, the output ion beam current decreases. The output ion beam is convergent at the optimum distance, while before and after this distance, the output ion beam is divergent.

![Graph showing output ion beam current versus the anode – cathode distance at $p= 3 \times 10^{-4}$ mm Hg, $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, and $I_d$ equals to 1 and 2 mA using Argon gas.](image)

**Fig.(16) Output ion beam current versus the anode – cathode distance at $p= 3 \times 10^{-4}$ mm Hg, $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, and $I_d$ equals to 1 and 2 mA using Argon gas.**
4.2- Determination of the optimum diameter of uncovered area of emission disc

In this experiment, the uncovered area diameter of emission disc, $D_{\text{uncovered em. disc}}$, is varied with values equal to 3, 4, 5, 6, and 7 mm at $d_{\text{A-C}}$ equals 6 mm, $D_{\text{em.}}$ equals 1.5 mm, and $d_{\text{em.-F.C.}}$ is fixed at 3 cm. The optimum uncovered area diameter of emission disc, $D_{\text{uncovered em. disc}}$ for stable discharge current and a maximum output ion beam current can be obtained.

4.2.1- Input characteristics

Figures (17), (18), (19), (20), and (21) show the discharge current, $I_d$ (mA), versus the discharge voltage, $V_d$ (KV), at different pressures $D_{\text{em}} = 1.5$ mm, $d_{\text{A-C}} = 6$ mm, $d_{\text{em.-F.C.}} = 3$ cm, and $D_{\text{uncovered em. disc}}$ is varied with values equal to 3, 4, 5, 6, and 7 mm using Argon gas. It is clear from the figures that the discharge current increases with increasing the discharge voltage and the discharge voltage starts at lower potential in case of high pressure ($6 \times 10^{-4}$ mmHg) than that in case of low pressure ($3 \times 10^{-4}$ mmHg).
Fig.(17) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered \ em. \ disc} = 3$ mm, $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, and different pressures using Argon gas.

Fig.(18) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered \ em. \ disc} = 4$ mm, $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, and different pressures using Argon gas.
Fig. (19) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered emission disc}} = 5$ mm, $D_{\text{em.}} = 1.5$ mm and $d_{\text{em.}}-F.C = 3$ cm, and different pressures using Argon gas.

Fig. (20) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered emission disc}} = 6$ mm, $D_{\text{em.}} = 1.5$ mm and $d_{\text{em.}}-F.C = 3$ cm, and different pressures using Argon gas.
Fig. (21) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 7$ mm, $D_{\text{em.}} = 1.5$ mm and $d_{\text{em.-F.C}} = 3$ cm, and different pressures using Argon gas.

4.2.2- Output ion beam characteristics

Figures (22), (23), (24), (25), and (26) show the output ion beam current, $I_b$ ($\mu$A), versus discharge voltage, $V_d$ (KV), at $D_{\text{em}} = 1.5$ mm, $d_{A-C} = 6$ mm, $d_{\text{em.-F.C}} = 3$ cm, $D_{\text{uncovered em. disc}}$ is varied with values equal to 3, 4, 5, 6, and 7 mm, and different pressures using Argon gas. It is clear that these figures are similar to the discharge current – discharge voltage curves. In order to increase the output ion beam current through the discharge; we must increase the number of electrons created by the ionization.
Fig.(22) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 3$ mm, $D_{\text{em.}} = 1.5$ mm, $d_{\text{em.} - F.C} = 3$ cm, and different pressures using Argon gas.

Fig.(23) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 4$ mm, $D_{\text{em.}} = 1.5$ mm, $d_{\text{em.} - F.C} = 3$ cm, and different pressures using Argon gas.
Fig. (24) Output ion beam current versus discharge voltage at $d_{A-C}=6$ mm, $D_{\text{uncovered em. disc}}=5$ mm, $D_{\text{em.}}=1.5$ mm, $d_{\text{em.-F.C}}=3$ cm, and different pressures using Argon gas.

Fig. (25) Output ion beam current versus discharge voltage at $d_{A-C}=6$ mm, $D_{\text{uncovered em. disc}}=6$ mm, $D_{\text{em.}}=1.5$ mm, $d_{\text{em.-F.C}}=3$ cm, and different pressures using Argon gas.
Fig. (26) Output ion beam current versus discharge voltage at \( \text{d}_{\text{A-C}} = 6 \text{ mm} \), \( \text{D}_{\text{uncovered em. disc}} = 7 \text{ mm} \), \( \text{D}_{\text{em.}} = 1.5 \text{ mm} \), \( \text{d}_{\text{em.-F.C}} = 3 \text{ cm} \), and different pressures using Argon gas.

Figures (27), (28), (29), (30), and (31) show the output ion beam current, \( I_b (\mu\text{A}) \), versus discharge current, \( I_d (\text{mA}) \), at \( D_{\text{em}} = 1.5 \text{ mm} \), \( \text{d}_{\text{em.-F.C.}} = 3 \text{ cm} \), \( \text{d}_{\text{A-C}} = 6 \text{ mm} \), and \( \text{D}_{\text{uncovered em. disc}} \) is varied with values equals 3, 4, 5, 6, and 7 mm, and different pressures using Argon gas. It is clear from the figures that the output ion beam current increases with increasing the discharge current and at \( P = 3 \times 10^{-4} \text{ mmHg} \) and \( \text{D}_{\text{uncovered em. disc}} = 5 \text{ mm} \), a maximum output ion beam current equals 106 \( \mu\text{A} \) can be obtained.
Fig.(27) Output ion beam current versus discharge current at $d_{A-C} = 6 \text{ mm}$, $D_{em.} = 1.5 \text{ mm}$, $D_{uncovered \ en. \ disc} = 3 \text{ mm}$, $d_{em.-F.C} = 3 \text{ cm}$, and different pressures using Argon gas.

Fig.(28) Output ion beam current versus discharge current at $d_{A-C} = 6 \text{ mm}$, $D_{em.} = 1.5 \text{ mm}$, $D_{uncovered \ en. \ disc} = 4 \text{ mm}$, $d_{em.-F.C} = 3 \text{ cm}$, and different pressures using Argon gas.
Fig. (29) Output ion beam current versus discharge current at \(d_{A-C} = 6\) mm, \(D_{em.} = 1.5\) mm, \(D_{uncovered\ em.\ disc} = 5\) mm, \(d_{em.- F.C} = 3\) cm, and different pressures using Argon gas.

Fig. (30) Output ion beam current versus discharge current at \(d_{A-C} = 6\) mm, \(D_{em.} = 1.5\) mm, \(D_{uncovered\ em.\ disc} = 6\) mm, \(d_{em.- F.C} = 3\) cm, and different pressures using Argon gas.
Fig.(31) Output ion beam current versus discharge current at \(d_{A-C} = 6\) mm, \(D_{em.} = 1.5\) mm, \(D_{uncovered\ em.\ disc} = 7\) mm, \(d_{em.-F.C} = 3\) cm, and different pressures using Argon gas.

4.2.3- The optimum diameter of uncovered area of emission disc

Figures (32) and (33) show the output ion beam current, \(I_b\) (\(\mu\)A), versus diameter of uncovered area of emission disc, \(D_{uncovered\ em.\ disc}\) (mm), at \(d_{A-C} = 6\) mm, \(D_{em.} = 1.5\) mm, \(d_{em.-F.C} = 3\) cm, \(I_d\) equal to 1 and 2 mA respectively, and different pressures using Argon gas. It is obvious from the curves that at \(P = 3 \times 10^{-4}\) mmHg, \(I_d = 1\) mA, and \(D_{uncovered\ em.\ disc} = 5\) mm, a maximum output ion beam current equal to 61 \(\mu\)A can be obtained. Also, at \(P = 3 \times 10^{-4}\) mmHg, \(I_d = 2\) mA, and \(D_{uncovered\ em.\ disc} = 5\) mm, a maximum output ion beam current equal to 106 \(\mu\)A can be obtained. While before and after this distance the output ion beam current decreases.
\[ I_d = 1 \text{ mA} \]

Fig. (32) Output ion beam current versus uncovered area diameter of emission disc, \( D_{\text{uncovered em. disc}} \) (mm), at \( d_{A-C} = 6 \text{ mm}, D_{\text{em.}} = 1.5 \text{ mm}, d_{\text{em.} - \text{F.C}} = 3 \text{ cm}, \text{ and } I_d = 1 \text{ mA}, \text{ and different pressures using Argon gas.} \]

\[ I_d = 2 \text{ mA} \]

Fig. (33) Output ion beam current versus uncovered area diameter of emission disc, \( D_{\text{uncovered em. disc}} \) (mm), at \( d_{A-C} = 6 \text{ mm}, D_{\text{em.}} = 1.5 \text{ mm}, d_{\text{em.} - \text{F.C}} = 3 \text{ cm}, \text{ and } I_d = 2 \text{ mA}, \text{ and different pressures using Argon gas.} \]
Figure (34) shows the output ion beam current, $I_b$ ($\mu$A), versus diameter of uncovered area of emission disc, $D_{uncovered\ \text{em.\ disc}}$ (mm), at $d_{A-C} = 6$ mm, $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, $I_d$ equal to 1 and 2 mA, and $P = 3 \times 10^{-4}$ mmHg using Argon gas. It is obvious from the curves that at $I_d = 2$ mA, $D_{uncovered\ \text{em.\ disc}} = 5$ mm, a maximum output ion beam current equal to 106 $\mu$A can be obtained. Also, at $I_d = 1$ mA, $D_{uncovered\ \text{em.\ disc}} = 5$ mm, a maximum output ion beam current equal to 61 $\mu$A can be obtained. While before and after this diameter, the output ion beam current decreases.

![Graph](image_url)
4.3- Determination of the optimum diameter of emission disc aperture

In this experiment, the diameter of the emission disc aperture, $D_{em.}$, is varied with values equal to 1.5, 2, 2.5, and 3 mm at $d_{A-C} = 6$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, and $d_{em.-F.C.}$ is fixed at 3 cm. The optimum $D_{em.}$ for stable discharge current and a maximum output ion beam current can be obtained.

4.3.1- Input characteristics

Figures (35), (36), (37), (38), and (39) show the discharge current, $I_d$ (mA), versus discharge voltage, $V_d$ (KV), at $D_{uncovered\ em.\ disc} = 5$ mm, $d_{A-C} = 6$ mm, $d_{em.-F.C.} = 3$ cm, $D_{em.}$ is varied with values equal to 1.5, 2, 2.5, and 3 mm, and different pressures using Argon gas. It is clear from the figures that the discharge current is increased by increasing the discharge voltage applied on the anode and the discharge voltage starts at lower potential in case of high pressure ($6 \times 10^{-4}$ mmHg) than that in case of low pressure ($3 \times 10^{-4}$ mmHg).
Fig. (35) Discharge current versus discharge voltage at \( d_{A-C} = 6 \text{ mm}, D_{\text{uncovered em. disc}} = 5 \text{ mm}, D_{\text{em.}} = 1.5 \text{ mm}, d_{\text{em.-F.C}} = 3 \text{ cm}, \) and different pressures using Argon gas.

Fig. (36) Discharge current versus discharge voltage at \( d_{A-C} = 6 \text{ mm}, D_{\text{uncovered em. disc}} = 5 \text{ mm}, D_{\text{em.}} = 2 \text{ mm}, d_{\text{em.-F.C}} = 3 \text{ cm}, \) and different pressures using Argon gas.
Fig.(37) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $D_{em} = 2.5$ mm, $d_{em-F.C} = 3$ cm, and different pressures using Argon gas.

Fig.(38) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $D_{em} = 3$ mm, $d_{em-F.C} = 3$ cm, and different pressures using Argon gas.
4.3.2- Output ion beam characteristics

Figures (39), (40), (41), and (42) show the output ion beam current, $I_b$ ($\mu$A), versus discharge voltage, $V_d$ (KV), at $d_{A-C} = 6$ mm, $d_{em.-F.C} = 3$ cm, $D_{uncovered\ em.\ disc} = 5$ mm, and the diameter of emission disc aperture, $D_{em.}$, is varied with values equals 1.5, 2, 2.5, and 3 mm, and different pressures using Argon gas. It is clear that these figures are similar in shape to the discharge current – discharge voltage curves. In order to increase the output ion beam current through the discharge; we must increase the number of electrons created by the ionization.

![Graph showing output ion beam current versus discharge voltage](image)

Fig.(39) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $D_{em.} = 1.5$ mm, $d_{em.-F.C} = 3$ cm, and different pressures using Argon gas.
Fig.(40) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $D_{em.} = 2$ mm, $d_{em.-F.C} = 3$ cm, and different pressures using Argon gas.

Fig.(41) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $D_{em.} = 2.5$ mm, $d_{em.-F.C} = 3$ cm, and different pressures using Argon gas.
Fig. (42) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $D_{em.} = 3$ mm, $d_{em. - F.C.} = 3$ cm, and different pressures using Argon gas.

Figures (43), (44), (45), and (46) show the output ion beam current, $I_b$ (µA), versus discharge current, $I_d$ (mA), at $D_{\text{uncovered em. disc}} = 5$ mm, $d_{em. - F.C.} = 3$ cm, $d_{A-C} = 6$ mm, and the diameter of emission disc aperture, $D_{em.}$, is varied with values equals 1.5, 2, 2.5, and 3 mm, and for different pressures using Argon gas. It is clear from the figures that the output ion beam current increases with increasing the discharge current and at $P = 5 \times 10^{-4}$ mmHg and $D_{em.} = 2.5$ mm, a maximum output ion beam current equals 462 µA can be obtained.
Fig.(43) Output ion beam current versus discharge current at $d_{A-C}=6$ mm, $D_{em.}=1.5$ mm, $D_{uncovered\ emission\ disc}=5\ mm$, $d_{em.-F.C}=3$ cm, and different pressures using Argon gas.

Fig.(44) Output ion beam current versus discharge current at $d_{A-C}=6$ mm, $D_{em.}=2$ mm, $D_{uncovered\ em.\ disc}=5\ mm$, $d_{em.-F.C}=3$ cm, and different pressures using Argon gas.
Fig. (45) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, $D_{uncovered~em.~disc} = 5$ mm, $d_{em-F.C} = 3$ cm, and different pressures using Argon gas.

Fig. (46) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em} = 3$ mm, $D_{uncovered~em.~disc} = 5$ mm, $d_{em-F.C} = 3$ cm, and different pressures using Argon gas.
4.3.3- The optimum diameter of emission disc aperture

Figure (47) shows the diameter of emission disc aperture, $D_{em.}$ (mm), versus output ion beam current, $I_b$ ($\mu$A), at $d_{A-C} = 6$ mm, $D_{uncovered \ em. \ disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, $I_d = 1$ mA, and different pressures using Argon gas. It is obvious from the curve that at $P = 3 \times 10^{-4}$ mmHg and $D_{em.} = 2.5$ mm, a maximum output ion beam current equal to 312 $\mu$A can be obtained. While before and after this distance the output ion beam current decreases.

Fig.(47) Output ion beam current versus diameter of emission disc aperture, $D_{em.}$ (mm), at $d_{A-C} = 6$ mm, $D_{uncovered \ em. \ disc} = 5$ mm , $d_{em.-F.C} = 3$ cm, and $I_d = 1$ mA , and different pressures using Argon gas.
4.4- Determination of the optimum emission disc-Faraday cup distance

In this experiment, the distance between the emission disc and Faraday cup, \( d_{\text{em.-F.C.}} \), is varied with values equals 1, 2, 3, and 4 mm at \( D_{\text{em.}} = 2.5 \text{ mm} \), \( d_{\text{A-C}} = 6 \text{ mm} \), and \( D_{\text{uncovered em. disc}} = 5 \text{ mm} \). The optimum \( d_{\text{em.-F.C.}} \) for stable discharge current and a maximum output ion beam current can be obtained.

4.4.1- Input characteristics

Figures (48), (49), (50) and (51) show the discharge current, \( I_d \) (mA), versus the discharge voltage, \( V_d \) (KV), at \( D_{\text{em.}} = 2.5 \text{ mm} \), \( d_{\text{A-C}} = 6 \text{ mm} \), \( D_{\text{uncovered em. disc}} = 5 \text{ mm} \), and \( d_{\text{em.-F.C.}} \) is varied with values equal to 1, 2, 3, and 4 mm for different pressures using Argon gas. It is clear from the figures that the discharge current is increased by increasing the discharge voltage applied on the anode and the discharge voltage starts at lower potential in case of high pressure (6 \( \times 10^{-4} \) mm Hg) than that in case of low pressure (4 \( \times 10^{-4} \) mm Hg).
Fig.(48) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.-F.C} = 1$ cm, and different pressures using Argon gas.

Fig.(49) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.-F.C} = 2$ cm, and different pressures using Argon gas.
**Fig. (50)** Discharge current versus discharge voltage at \(d_{A-C} = 6 \text{ mm}, D_{em.} = 2.5 \text{ mm}, D_{uncovered \text{ em. disc}} = 5 \text{ mm}, d_{em. - F.C} = 3 \text{ cm}, \) and different pressures using Argon gas.

**Fig. (51)** Discharge current versus discharge voltage at \(d_{A-C} = 6 \text{ mm}, D_{em.} = 2.5 \text{ mm}, D_{uncovered \text{ em. disc}} = 5 \text{ mm}, d_{em. - F.C} = 4 \text{ cm}, \) and different pressures using Argon gas.
4.4.2- Output ion beam characteristics

Figures (52), (53), (54), and (55) show the output ion beam current, \( I_b (\mu A) \), versus discharge voltage, \( V_d (KV) \), at \( d_{A-C} = 6 \text{ mm} \), \( D_{em.} = 2.5 \text{ mm} \), \( D_{uncovered \ em. \ disc} = 5 \text{ mm} \), the distance between the emission disc and Faraday cup, \( d_{em.-F.C.} \), is varied with values equals 1, 2, 3, and 4 mm, and for different pressures using Argon gas. It is clear that these figures are similar in shape to the discharge voltage – discharge current curves. In order to increase the output ion beam current through the discharge; we must increase the number of electrons created by the ionization.

![Graph showing output ion beam current versus discharge voltage](image)

**Fig.(52)** Output ion beam current versus discharge voltage at \( d_{A-C} = 6 \text{ mm} \), \( D_{em.} = 2.5 \text{ mm} \), \( D_{uncovered \ em. \ disc} = 5 \text{ mm} \), \( d_{em.-F.C.} = 1 \text{ cm} \), and different pressures using Argon gas.
Fig. (53) Output ion beam current versus discharge voltage at $d_{\text{A-C}} = 6$ mm, $D_{\text{em}} = 2.5$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $d_{\text{em-F.C}} = 2$ cm, and different pressures using Argon gas.

Fig. (54) Output ion beam current versus discharge voltage at $d_{\text{A-C}} = 6$ mm, $D_{\text{em}} = 2.5$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $d_{\text{em-F.C}} = 3$ cm, and different pressures using Argon gas.
Fig. (55) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.-F.C} = 4$ cm, and different pressures using Argon gas.

Figures (56), (57), (58), and (59) show the output ion beam current, $I_b$ ($\mu$A), versus discharge current, $I_d$ (mA), at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, the distance between the emission disc and Faraday cup, $d_{em.-F.C}$, is varied with values equals 1, 2, 3, and 4 mm, and for different pressures using Argon gas. It is clear from the figures that the output ion beam current increases with increasing the discharge current and at $P = 5 \times 10^{-4}$ mmHg and $d_{em.-F.C} = 3$ cm, a maximum output ion beam current equals 462 $\mu$A can be obtained.
Fig. (56) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.-F.C} = 1$ cm, and different pressures using Argon gas.

Fig. (57) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.-F.C} = 2$ cm, and different pressures using Argon gas.
Fig.(58) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, $D_{uncovered\ emission\ disc} = 5$ mm, $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, and different pressures using Argon gas.

Fig.(59) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, and different pressures using Argon gas.
4.4.3- The optimum distance between emission disc-Faraday cup

Figures (60) and (61) show output ion beam current, $I_b$ (µA), versus the distance between the emission disc and Faraday cup, $d_{em.-F.C.}$, at $d_{A-C} = 6$ mm, $D_{uncovered em. disc} = 5$ mm, $D_{em.} = 2.5$ mm, $I_d$ equal to 0.5 and 1 mA, and for different pressures using Argon gas. It is obvious from the curves that at $P = 5 \times 10^{-4}$ mmHg and $d_{em.-F.C.} = 3$ cm, a maximum output ion beam current equal to 189, 462 µA respectively can be obtained. While before and after this distance the output ion beam current decreases.

![Graph](image-url)

Fig.(60) Output ion beam current versus the distance between the emission disc and Faraday cup, $d_{em.-F.C.}$, at $d_{A-C} = 6$ mm, $D_{uncovered em. disc} = 5$ mm, $D_{em.} = 2.5$ mm, and $I_d = 0.5$ mA, and different pressures using Argon gas.
Fig. (61) Output ion beam current versus the distance between the emission disc and Faraday cup, $d_{em.-F.C.}$, at $d_{A-C} = 6$ mm, $D_{uncovered \ em. \ disc} = 5$ mm, $D_{em.} = 2.5$ mm, and $I_d = 1$ mA, and different pressures using Argon gas.

Figures (62) shows output ion beam current, $I_b$ ($\mu$A), versus the distance between the emission disc and Faraday cup, $d_{em.-F.C.}$ (cm), at $d_{A-C} = 6$ mm, $D_{uncovered \ em. \ disc} = 5$ mm, $D_{em.} = 2.5$ mm, $I_d$ equal to 0.5 and 1 mA, and for $P = 5 \times 10^{-4}$ mm Hg using Argon gas. It is obvious from the curves that at $I_d = 1$ mA, $d_{em.-F.C} = 3$ cm, a maximum output ion beam current equal to 189 $\mu$A can be obtained. Also, at $I_d = 0.5$ mA, $d_{em.-F.C} = 3$ cm, a maximum output ion beam current equal to 105 $\mu$A can be obtained. While before and after this distance, the output ion beam current decreases.
Fig.(62) Output ion beam current versus the distance between the emission disc and Faraday cup, $\text{d}_{\text{em.-F.C.}}$ at $\text{d}_{\text{A-C}} = 6 \text{ mm}$, $\text{D}_{\text{uncovered em. disc}} = 5 \text{ mm}$, and $I_d$ equal to 0.5 and 1 mA, and for $P = 5 \times 10^{-4} \text{ mm Hg}$ using Argon gas.

Fig.(63) The effect of Argon ion beam on Copper Faraday cup for one hour without magnetic field.
4.5- Determination of the optimum strength of permanent magnetic field

In this experiment, the strength of permanent magnetic field, B is varied with values equals 50, 100, 200, 230, 300, 330, and 400 Gauss at \( D_{em.} = 2.5 \) mm, \( d_{A-C} = 6 \) mm, \( d_{em.-F.C} = 3 \) cm, and \( D_{uncovered \ em. \ disc} = 5 \) mm. The magnetic field is placed at 1.5 cm from the anode body. The optimum magnetic field strength for stable discharge current and a maximum output ion beam current can be obtained.

4.5.1- Input characteristics

Figures (64), (65), (66), (67), (68), (69), and (70) show the discharge current, \( I_d \) (mA), versus the discharge voltage, \( V_d \) (KV), at \( D_{em} = 2.5 \) mm, \( d_{A-C} = 6 \) mm, \( D_{uncovered \ em. \ disc} = 5 \) mm, and \( d_{em.-F.C.} = 3 \) cm, B is varied with values equal to 50, 100, 200, 230, 300, 330, and 400 Gauss for different pressures using Argon gas. It is clear from the figures that the discharge current is increased by increasing the discharge voltage applied on the anode and the discharge voltage starts at lower potential in case of high pressure \( (9 \times 10^{-4} \) mmHg) than that in case of low pressure \( (6 \times 10^{-4} \) mmHg).
Fig. (64) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}}$ = 5 mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em. - F.C}} = 3$ cm, $B = 50$ G, and different pressures using Argon gas.

Fig. (65) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}}$ = 5 mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em. - F.C}} = 3$ cm, $B = 100$ G, and different pressures using Argon gas.
Fig. (66) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em.} - F.C} = 3$ cm, $B = 200$ G, and different pressures using Argon gas.

Fig. (67) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em.} - F.C} = 3$ cm, $B = 230$ G, and different pressures using Argon gas.
Fig.(68) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em.- F.C}} = 3$ cm, $B = 300$ G, and different pressures using Argon gas.

Fig.(69) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em.- F.C}} = 3$ cm, $B = 330$ G, and different pressures using Argon gas.
Fig.(70) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $D_{\text{em.}} = 2.5$ mm, $d_{\text{em. - F.C}} = 3$ cm, $B = 400$ G, and different pressures using Argon gas.

4.5.2- Output ion beam characteristics

Figures (71), (72), (73), (74), (75), (76), and (77) show output ion beam current, $I_b$ ($\mu$A), versus the discharge current, $I_d$ (mA), at $d_{A-C} = 6$ mm, $D_{\text{em.}} = 2.5$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $d_{\text{em. - F.C}} = 3$ cm, $B$ is varied with values equals 50, 100, 200, 230, 300, 330, and 400 Gauss and for different pressures using Argon gas. It is clear from the figures that the output ion beam current increases with increasing the discharge current and at $P = 6 \times 10^{-4}$ mmHg and $B = 300$ G, a maximum output ion beam current equals 298 $\mu$A can be obtained.
Fig.(71) Output ion beam current versus discharge current at $d_{A-C}=6$ mm, $D_{em.}=2.5$ mm, $D_{uncovered\,em.\,disc}=5$ mm, $d_{em.-F.C}=3$ cm, $B=50$ G, and different pressures using Argon gas.

Fig.(72) Output ion beam current versus discharge current at $d_{A-C}=6$ mm, $D_{em.}=2.5$ mm, $D_{uncovered\,em.\,disc}=5$ mm, $d_{em.-F.C}=3$ cm, $B=100$ G, and different pressures using Argon gas.
Fig.(73) Output ion beam current versus discharge current at \( d_{A-C} = 6 \text{ mm}, D_{\text{em.}} = 2.5 \text{ mm}, D_{\text{uncovered em. disc}} = 5 \text{ mm}, d_{\text{em. – F.C}} = 3 \text{ cm}, B = 200 \text{ G}, \) and different pressures using Argon gas.

Fig.(74) Output ion beam current versus discharge current at \( d_{A-C} = 6 \text{ mm}, D_{\text{em.}} = 2.5 \text{ mm}, D_{\text{uncovered em. disc}} = 5 \text{ mm}, d_{\text{em. – F.C}} = 3 \text{ cm}, B = 230 \text{ G}, \) and different pressures using Argon gas.
Fig. (75) Output ion beam current versus discharge current at $d_{A-C}=6$ mm, $D_{em.}=2.5$ mm, $D_{uncovered\ em.\ disc}=5$ mm, $d_{em.-F.C}=3$ cm, $B=300$ G, and different pressures using Argon gas.

Fig. (76) Output ion beam current versus discharge current at $d_{A-C}=6$ mm, $D_{em.}=2.5$ mm, $D_{uncovered\ em.\ disc}=5$ mm, $d_{em.-F.C}=3$ cm, $B=330$ G, and different pressures using Argon gas.
4.5.3 - The optimum strength of permanent magnetic field

Figure (78) shows output ion beam current, \( I_b \) (\( \mu A \)), versus the magnetic field strength, \( B \) (Gauss), at \( d_{A-C} = 6 \text{ mm}, D_{\text{em.}} = 2.5 \text{ mm}, D_{\text{uncovered em. disc}} = 5 \text{ mm}, d_{\text{em.-F.C}} = 3 \text{ cm}, B = 400 \text{ G}, \) and for different pressures using Argon gas. It is obvious from the curves that at \( P = 7 \times 10^{-4} \text{ mmHg} \) and \( B = 300 \text{ Gauss} \), a maximum output ion beam current equal to 190 \( \mu A \) can be obtained. While before and after this distance the output ion beam current decreases.
Fig. (78) Output ion beam current versus magnetic field strength at \( d_{A-C} = 6 \) mm, \( D_{\text{uncovered em. disc}} = 5 \) mm, \( D_{\text{em.}} = 2.5 \) mm, \( d_{\text{em.–F.C}} = 3 \) cm, and different pressures using Argon gas.

4.5.4-Comparison between output ion beam current value with and without magnet

Figure (79) shows the relation between the output ion beam current, \( I_b \) (\( \mu \)A), versus the discharge current, \( I_d \) (mA), at \( P = 6 \times 10^{-4} \) mmHg, optimum operating conditions, with and without the effect of magnetic field using Argon gas. It is clear that at \( I_d = 1.2 \) mA and \( B = 300 \) Gauss, a maximum output ion beam current equal to 300 \( \mu \)A can be obtained, while at \( B = 0 \), a maximum output ion beam current equal to 150 \( \mu \)A can be obtained. It can be concluded that at \( P = 6 \times 10^{-4} \) mmHg and \( B = 300 \) Gauss, the output ion beam current value is twice its value without magnet. Figure (63) shows the effect of Argon ion beam on Copper Faraday cup for one hour without
magnetic field. Figure (80) shows the effect of Argon ion beam on Copper Faraday cup for one hour with magnetic field of strength $B = 300$ Gauss.

![Graph showing discharge current vs output ion beam current at optimum operating conditions and $P = 6 \times 10^{-4}$ mmHg with $B = 300$ G and without magnet using Argon gas.]

![Image showing the effect of Argon ion beam on Copper Faraday cup for one hour with magnetic field of strength $B = 300$ Gauss.]

Fig. (79) Output ion beam current versus discharge current at optimum operating conditions and $P = 6 \times 10^{-4}$ mmHg with $B = 300$ G and without magnet using Argon gas.

Fig. (80) The effect of Argon ion beam on Copper Faraday cup for one hour with magnetic field of strength $B = 300$ Gauss.
4.6- The optimum parameters of PIG ion source using Nitrogen gas

In this experiment, we made the optimized parameters of cold cathode Penning ion source using Nitrogen gas.

4.6.1- Input characteristics

Figure (81) shows the discharge current, $I_d$ (mA), versus the discharge voltage, $V_d$ (KV), at $D_{em} = 2.5$ mm, $d_{A-C} = 6$ mm, $D_{uncovered\,em.\,disc} = 5$ mm, and $d_{em.-F.C.} = 3$ cm, magnetic field strength, $B$, equals 300 Gauss for different pressures using Nitrogen gas. It is clear from the figures that the discharge current is increased by increasing the discharge voltage applied on the anode and the discharge voltage starts at lower potential in case of high pressure ($9 \times 10^{-4}$ mmHg) than that in case of low pressure ($5 \times 10^{-4}$ mmHg).

![Graph showing discharge current versus discharge voltage at different pressures](image-url)
4.6.2- Output ion beam characteristics

Figure (82) shows output ion beam current, $I_b$ (µA), versus the discharge voltage, $V_d$ (KV), at $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, $D_{\text{uncovered em. disc}} = 5$ mm, $d_{em - F.C} = 3$ cm, magnetic field strength, $B$, equals 300 Gauss, and for different pressures using Nitrogen gas. It is clear that these figures are similar in shape to the discharge voltage – discharge current curves. In order to increase the output ion beam current through the discharge; we must increase the number of electrons created by the ionization.

![Graph showing output ion beam current versus discharge voltage with different pressures and pressures using Nitrogen gas.](image)

Fig. (82) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm , $D_{\text{uncovered em. disc}} = 5$ mm, $d_{em - F.C} = 3$ cm, $B = 300$ G, and different pressures using Nitrogen gas.
Figure (83) shows output ion beam current, $I_b$ ($\mu$A), versus the discharge current, $I_d$ (mA), at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered \ em. \ disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, magnetic field strength, $B$, equals 300 Gauss for different pressures using Nitrogen gas. It is clear from the figures that the output ion beam current increases with increasing the discharge current and at $P = 5 \times 10^{-4}$ mm Hg, a maximum output ion beam current equals 241 $\mu$A can be obtained.

![Graph](image)

Fig.(83) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered \ em. \ disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, $B = 300$ G, and different pressures using Nitrogen gas.
4.7- The cold cathode Penning ion source characteristics using Nitrogen and Argon gases

In this experiment, we made the optimized parameters of the cold cathode Penning ion source using Argon and Nitrogen gases.

4.7.1- Input characteristics

Figure (84) shows discharge current, $I_d$ (mA), versus discharge voltage, $V_d$ (KV), the at $D_{em} = 2.5$ mm, $d_{A-C} = 6$ mm, $D_{uncovered em. disc} = 5$ mm, and $d_{em.-F.C} = 3$ cm, magnetic field strength, $B$, equals 300 Gauss, $P = 9 \times 10^{-4}$ mm Hg using Argon and Nitrogen gases. It is clear from this figure that the discharge current is increased by increasing the discharge voltage. Nitrogen gas ionization starts at lower potential than that of Argon gas.

![Figure 84](image.png)

**Fig.(84) Discharge current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{uncovered em. disc} = 5$ mm, $D_{em} = 2.5$ mm, $d_{em.-F.C} = 3$ cm, $B = 300$ G, and $P = 9 \times 10^{-4}$ mm Hg using Nitrogen and Argon gases.**
4.7.2- Output ion beam characteristics

Figure (85) shows output ion beam current, \( I_b \) (µA), versus discharge voltage, \( V_d \) (KV), at \( d_{A-C} = 6 \) mm, \( D_{em.} = 2.5 \) mm, \( D_{uncovered \ em. \ disc} = 5 \) mm, \( d_{em.-F.C} = 3 \) cm, magnetic field strength, \( B \), equals 300 Gauss, and \( P = 9 \times 10^{-4} \) mm Hg using Nitrogen and Argon gases. It is clear that this figure is similar in shape to the discharge voltage – discharge current curves. In order to increase the output ion beam current through the discharge; we must increase the number of electrons created by the ionization. Argon gas has higher output ion beam current than Nitrogen gas.

![Graph](image.png)

Fig.(85) Output ion beam current versus discharge voltage at \( d_{A-C} = 6 \) mm, \( D_{em.} = 2.5 \) mm, \( D_{uncovered \ em. \ disc} = 5 \) mm, \( d_{em.-F.C} = 3 \) cm, \( B = 300 \) G, and \( P = 9 \times 10^{-4} \) mm Hg using Nitrogen and Argon gases.
Figure (86) shows output ion beam current, $I_b$ (µA), versus discharge current, $I_d$ (mA), at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered em. disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, magnetic field strength, $B$, equals 300 Gauss, and $P = 9 \times 10^{-4}$ mmHg using Nitrogen and Argon gases. It is clear from this figure that the output ion beam current increases with increasing the discharge current and a maximum output ion beam current of Argon equals 169 µA can be obtained, while for Nitrogen is 134 µA.

Fig.(86) Output ion beam current versus discharge voltage at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered em. disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, $B = 300$ G, and $P = 9 \times 10^{-4}$ mm Hg using Nitrogen and Argon gases.
4.8 - Effect of negative voltage on Faraday cup

In this experiment, the negative voltage is affected on Faraday cup using Argon gas, the output ion beam current is increased. Figure (87) shows output ion beam current, $I_b (\mu A)$, versus discharge current, $I_d (mA)$, at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered \; em. \; disc} = 5$ mm, $d_{em.-F.C} = 3$ cm , magnetic field strength, $B$, equals 300 Gauss for different negative voltage applied on Faraday cup using Argon gas. The higher negative voltage on Faraday cup has high ion beam current.

![Figure 87](image)

Fig.(87) Output ion beam current versus discharge current at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered \; em. \; disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, $B = 300$ G, and different negative voltages applied on Faraday cup using Argon gas.
Figure (88) shows the output ion beam current versus the negative voltage applied on Faraday cup the using Argon gas. It is clear that the higher ion beam current is at higher discharge current value.

There are two minimum points ($V_{ng} = -500$, -1500 V) at which the ion beam current decreased and before and after them, the output ion beam current increased. There is a maximum point ($V_{ng} = -1000$ V), at which the output ion beam current increased to reach 350 µA for $I_d = 9$ mA. At $I_d = 0.4$ mA, the output ion beam current and negative voltage relation is nearly linear. But as the value of discharge current increased, the maximum value at $V_{ng} = -1000$ V is increased. This is due to the plasma intensity is increased, the output ion beam current increased by applying negative voltage applied on Faraday cup.
### Fig. (88) Output ion beam current versus negative voltage applied on Faraday cup at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered \, em. \, disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, $B = 300$ G, and different discharge current using Argon gas.

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### 4.9 - Effect of energy analyzer on extracted ion beam current

In this experiment, the energy analyzer consists of retarding grid and screen grid. This energy analyzer is placed between the emission disc and Faraday cup. The retarding grid is positively and negatively potential, in case of retarding ions and electrons respectively. The dimensions of this analyzer are:
- Emission disc- retarding grid distance equals 1 cm.
- Retarding grid – screen grid distance equals 1 cm.
- Screen grid – Faraday cup distance equals 1 cm.
- Diameters of two grids equal 1 cm.
- Diameter of holes equal 2 mm.

4.9.1- Ion retarding

In this experiment, the retarding grid is connected to positive potential, while the emission disc and screen grid are connected to ground. Figure (89) shows the relation between the voltage applied the retarding grid $V_{ret}$ (V) versus the output ion beam current at the optimized parameters of the ion source, special pressure $P = 9 \times 10^{-4}$ mm Hg, and two values of discharge voltage (2 and 3 KV) using Argon gas. It is clear from this figure this relation is higher at $V_d = 3$ KV than $V_d = 2$ KV. At $V_d = 2$ KV, output ion beam current is 4 $\mu$A for voltage equals 200 V applied on retarding grid. The output ion beam current decreases for retarding voltage $< $ discharge voltage, and saturated for retarding voltage $\geq$ discharge voltage. Figure (90) shows the effect of Argon ion beam on Copper Faraday cup at optimized parameters in case of positive potential applied on the retarding grid.
Fig. (89) Output ion beam current versus voltage applied on retarding grid at $d_{AC} = 6$ mm, $D_{em} = 2.5$ mm, $D_{uncovered \, em. \, disc} = 5$ mm, $d_{em - F.C} = 3$ cm, $B = 300$ G, and $P = 9 \times 10^{-4}$ mm Hg using discharge voltages 2 and 3 KV Argon gas.

Fig. (90) the effect of Argon ion beam on Copper Faraday cup at optimized parameters in case of retarding grid is positive potential.
4.9.2- Energy distribution

Figure (91) shows the energy distribution for the optimized parameters of the ion source at pressure equals $9 \times 10^{-4}$ mmHg, discharge voltage equals 2 and 3 KV, and using Argon gas. It is clear from the figure that the energy distribution is almost independently of the discharge voltage. The ions emitting from plasma boundary and moving towards the ion exit aperture, accelerates in the field between the plasma boundary and the emission disc. When it becomes fast and collide with the gas atoms, the collision can result in an ion extracting an electron from gas atom, resulting in it becoming a fast neutral atom while the slow atom becomes a slow positive ion. This process does not change the number of the ions in the system, is called charge transfer process with general form:

$$X^+ \text{ (Energetic ion)} + X \text{ (Slow atom)} \rightarrow X^+ \text{ (Slow ion)} + X \text{ (Fast atom)}$$
Fig. (91) the energy distribution at the optimized parameters at pressure equals $9 \times 10^{-4}$ mmHg, different discharge voltage, and using Argon gas.

4.10 – Paschen curve

The law essentially states that, at higher pressures (above a few torr) the breakdown characteristics of a gap are a function (generally not linear) of the product of the gas pressure and the gap length, usually written as $V = f(pd)$, where $p$ is the pressure, $d$ is the gap distance, and $V$ is the breakdown voltage.
4.10.1- Without applying magnetic field

Figure (92) shows the relation between the pressure (torr) multiplied by gap distance between the anode – cathode (cm) versus the discharge voltage (KV) at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\,em.\,disc} = 5$ mm, $d_{em.-\,F.C} = 3$ cm, and discharge current varies with values 0.5, 0.6, 0.7, 0.8, 0.9, and 1 mA without applying magnetic field using Argon gas. It is clear that discharge voltage decreases as the pressure is high. The lower relation occurs at lower discharge current $I_d = 0.5$ mA.

**Fig.(92) Pressure multiplied by gap distance versus discharge current at $d_{A-C}= 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\,em.\,disc} = 5$ mm, $d_{em.-\,F.C} = 3$ cm, $B = 0$, and different discharge current using Argon gas.**
4.10.2- With applying magnetic field

Figure (93) shows the relation between the pressure (torr) multiplied by gap distance between the anode – cathode (cm) versus the discharge voltage (KV) at \(d_{A-C} = 6\) mm, \(D_{em.} = 2.5\) mm, \(D_{uncovered\ \text{em.\ disc}} = 5\) mm, \(d_{em.-\ F.C} = 3\) cm, and discharge current varies with values 0.5, 0.6, 0.7, 0.8, 0.9, and 1 mA with applying magnetic field \((B = 300\ \text{G})\) using Argon gas. It is clear that discharge voltage decreases as the pressure is high. The lower relation occurs at lower discharge current \(I_d = 0.5\) mA.

![Graph showing the relation between pressure multiplied by gap distance versus discharge current.](image)

**Fig.(93)** Pressure multiplied by gap distance versus discharge current at \(d_{A-C} = 6\) mm, \(D_{em.} = 2.5\) mm, \(D_{uncovered\ \text{em.\ disc}} = 5\) mm, \(d_{em.-\ F.C} = 3\) cm, \(B = 300\ \text{G}\), and different discharge current using Argon gas.
4.10.3- Without and with applying magnetic field

Figure (94) shows the relation between the discharge voltage, $V_d$ (KV), versus the discharge current, $I_d$ (mA), at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.- F.C} = 3$ cm, $P = 6 \times 10^{-4}$ mm Hg without and with applying magnetic field using Argon gas. It is clear that as the discharge voltage increases, the discharge current increases. With applying magnetic field, the ionization starts at higher discharge voltage than without applying magnetic field.

![Graph showing discharge voltage versus discharge current](image)

**Fig.(94)** Discharge voltage versus discharge current at $d_{A-C} = 6$ mm, $D_{em.} = 2.5$ mm, $D_{uncovered\ em.\ disc} = 5$ mm, $d_{em.- F.C} = 3$ cm, $P = 6 \times 10^{-4}$ mm Hg, without and with applying magnetic field using Argon gas.
4.11 – Efficiency of this ion source

In this experiment, we can determine the efficiency of the ion source. By drawing the relation between the pressure of the Argon gas versus the output ion beam current and discharge current ratio. Figure (95) shows the relation between the gas pressure (mmHg) versus the efficiency of the ion source at $V_d = 3.92$ KV, optimized parameters, and using Nitrogen and Argon gases. It is clear that the ion source is more efficient for Argon than Nitrogen gas.

![Graph showing efficiency of ion source](image-url)

Fig.(95) Gas pressure versus ion source efficiency at $d_{A-C} = 6$ mm, $D_{em} = 2.5$ mm, $D_{uncovered em. disc} = 5$ mm, $d_{em.-F.C} = 3$ cm, $V_d = 3.92$ KV, with applying magnetic field using Nitrogen and Argon gases.
4.12 – Perveance

Figure (96) shows the relation between the discharge current, $I_d$ (mA), versus the perveance, $\left[ \frac{I_b}{V_d^{3/2}} \right] \times 10^5$ in $(A/V^{3/2})$, at the optimized parameters of the ion source, pressure equals $7 \times 10^{-4}$ mmHg, and using Nitrogen and Argon gases. It is clear that by increasing the discharge current, the perveance increases and at discharge current equals 1.3 mA, the perveance reaches $62.3 \times 10^6$ $(A/V^{3/2})$ and $49 \times 10^6$ $(A/V^{3/2})$ for Argon and Nitrogen gases respectively. The perveance in case of Argon gas is higher than that in case of Nitrogen gas.

![Perveance versus discharge current graph](image)

**Fig.(96) Perveance versus the discharge current at the optimized parameters of ion source, pressure equals $7 \times 10^{-4}$ mmHg, and using Argon and Nitrogen gases.**
4.13 – Operating time of this ion source

Figure (97) shows the output ion beam current, $I_b$ (µA), versus the exposed time, $t$ (min.), at the optimized parameters of the ion source, pressure equals $7 \times 10^{-4}$ mmHg, and using Argon gas bombarded with Molybdenum specimen. It is clear that the output ion beam current is nearly constant ranging from 130 to 163 µA during the exposed time. It means that the operating time of this ion source is two hours, depending on the insulating materials.

Fig.(97) Output ion beam current versus the exposed time at the optimized parameters of the ion source, pressure equals $7 \times 10^{-4}$ mmHg, and using Argon gas bombarded with Molybdenum specimen.
4.14– Comparison between theoretical and experimental results

By substituting in equation (2.11) presented in chapter (2) by the voltage, charge state, and mass (a.m.u) values for Argon gas, then the theoretical values of output ion beam current can be obtained. Figure (98) shows the output ion beam current, $I_b$ (µA), versus the discharge current, $I_d$ (mA), at the optimized parameters of the ion source, pressure equals $8 \times 10^{-4}$ mmHg, and for experimental and theoretical results using Argon gas. It is clear that there is symmetry in the values of output ion beam current between the experimental data and the theoretical calculation.

![Graph](image)

Fig.(98) Output ion beam current versus the discharge current at the optimized parameters of the ion source, pressure equals $8 \times 10^{-4}$ mmHg, and for experimental and theoretical results using Argon gas.
Finally, after we determined the optimized parameters of a cold
cathode Penning ion source which give maximum output ion beam
current. This ion source is used in applications, specially in polymers
specimens.

5.1- Introduction

Ion beams have been used to modify basic processes that control
thin film growth and morphology. In recent years, there has been a
rapid growth in the utilization of ion sources for a variety of
applications, including nuclear physics, isotopes separators,
multiampere beams for fusion applications and for industrial
production applications. Also they are useful tools in ion
implantation, ion sputtering Behrisch et al. [88], ion etching, ion
beam machining, ion beam surface modification Rodriguez et al.
[89] and neutron generators. As a consequence of this growth, there
has been the need for a better understanding of the factors which
affect the optical quality Sadahiro et al. [90] of ion beams.

Ion beams have been used for many years in a variety of
scientific experiments. More recently they have emerged into use in
engineering applications and even in production, for example,
sputtering deposition and removal in semiconductor device
manufacture Hall [91], fine surface polishing, by ion- implantation
doping of semiconductor materials and devices and by the use of ion
beams for propulsion of space vehicles. Ion beams offer certain
unique advantages that are resulting in their increasing use for semiconductor and other microelectronic applications.

Ions are heavy they have $10^3$ to $10^6$ times the mass of an electron. Thus for a given energy, an ion has approximately $10^2$ to $10^4$ times greater momentum than an electron. As a result of this characteristic, ions can produce quantitatively different effects in interaction with crystal lattices.

5.2- Polymers

5.2.1- Brief history of polymers

As far back as 1839, Charles Goodyear first improved the elastic properties of natural rubber by heating with sulfur (vulcanization). The first synthetic polymer, a phenol-formaldehyde polymer, was introduced under the name “Bakelite”, by Leo Baekeland in 1909. Rayon, the first synthetic fiber was developed as a replacement for silk in 1911. It was not until the 1930s that the macromolecule model of rubber was understood. After World War II and through the 1950s rapid developments in synthetic polymers were made.

5.2.2- PM – 355 polymer

In this experiment, the ion beam of argon gas is bombarded to PM-355 polymer specimens at different times. Figure (1) shows the absorbance versus the fluence at optimized parameters of this ion source and different wavelengths.
Fig.(1) Absorbance versus fluence at optimized ion source parameters and different wave lengths using argon ion beam bombarded to PM- 355 polymer specimen.

It is clear from this figure that the absorbance increases as the fluence increases. It means that there is cross linking occurs in polymer.
In this work, the design, construction, and operation of a new shape of cold Molybdenum cathode Penning ion source were made in the Accelerators and Ion Sources Department, Nuclear Research Center, Atomic Energy Authority, Egypt.

The new shape of cold cathode Penning ion source consists of Copper cylindrical hollow anode of 40 mm length, 12 mm diameter, and has two cone ends of 15 mm length, 22 mm upper cone diameter and 12 mm bottom cone diameter. The two movable Molybdenum cathodes are fixed in Perspex insulator and placed symmetrically at two ends of the anode. The Copper emission disc of 2 mm thickness and has central aperture of different diameters is placed at the middle of the anode for ion beam exit. The inner surface of the emission disc is isolated from the anode by Perspex insulator except an area of diameter equals 5 mm (the optimum) to confine the discharge in this area. The movable Faraday cup is placed at different distances from the emission electrode aperture used to collect the output ion beam extracted from the ion source.

It has been found that the glow discharge started between the two cathodes and the anode which acts as a continuous feeding source of the ions to the system. With the increase of the anode potential, the plasma boundary layer is extended to the cathode where the glow discharge takes place. The extracted boundary layer of the plasma is affected by further increase of the potential, which is detected by an increase of the output ion beam current. The ion beam is extracted
from the discharge region through central aperture of emission electrode equals 2.5 mm.

From the experimental results of this ion source using Argon gas. It can be concluded that the optimum operating conditions are:

- Anode- cathode distance equal to 6 mm
- The emission electrode aperture diameter equal to 2.5 mm
- The emission electrode aperture – Faraday cup equal to 3cm
- The inner diameter of uncovered emission electrode equal to 5mm.

It can be concluded that at the optimum operating conditions, discharge current equals 2 mA, and pressure equals $4 \times 10^{-4}$ mmHg, a maximum output ion beam current equal to 540 µA can be produced.

The effect of Samarium - Cobalt permanent magnet on the discharge characteristics of this ion source was determined using Argon gas. It can be concluded that at pressure equal to $6 \times 10^{-4}$ mm Hg, discharge current equal to 1.4 mA, and permanent magnet of intensity equal to 300 Gauss, the output ion beam current value is twice its value without magnet.

The effect of negative voltage applied on the Faraday cup on the output ion beam current from the ion source using Argon gas was determined. It can be concluded that at pressure equal to $5 \times 10^{-4}$ mmHg, discharge current equal to 2 mA, permanent magnet of
intensity equal to 300 Gauss, and $V_{\text{neg.}} = -1000$ Volt, a maximum output ion beam current equal to 350 $\mu$A can be obtained.

The energy spectrum of the positive ions emerging from the new shape ion source has been measured. The low energy ions are probably due to the charge exchange process taking place inside the ion source. The symmetrical charge transfer process has the general form:

$$X^+ (\text{Energetic ions}) + X (\text{Slow atom}) \rightarrow X^+ (\text{Slow ions}) + X (\text{Fast atom})$$

The effect of retarding voltage applied on the retarding grid, while the emission electrode and screen grid are connected to the ground was determined. It can be concluded that at the optimum operating conditions of this ion source, different discharge voltages (2 KV and 3 KV), pressure equal to $9 \times 10^{-4}$ mmHg, and permanent magnet of intensity equal to 300 Gauss, the output ion beam current decreases by increasing the retarding voltage and starts to be constant at retarding voltage greater than the discharge voltage.

The ion source efficiency was determined at the optimum operating conditions, discharge voltage equal to 3.92 KV and different pressures using Nitrogen and Argon gases. It can be concluded that the ion source efficiency reaches 35% and 22% using Argon and Nitrogen gases respectively.
The effect of discharge current on the perveance of this ion source was determined. It can be concluded that at the optimum conditions parameters, pressure equal to $7 \times 10^{-4}$ mmHg, permanent magnet of intensity equals 300 Gauss, the perveance is increased by increasing the discharge current and reaches $62.7 \times 10^5$ A/ V$^{3/2}$ and $40.4 \times 10^5$ A/ V$^{3/2}$ using Argon and Nitrogen gases respectively.

Also, it can be concluded that the operating time of this ion source is two hours at the optimum operating conditions, pressure equals $7 \times 10^{-4}$ mmHg, permanent magnet of intensity equals 300 Gauss, discharge voltage equals 5 KV, and discharge current equals 1.8 mA.

Finally, it can be concluded that the new shape of cold cathode Penning ion source can be used for different applications such as sputtering, materials surface modification and thin films deposition of different materials.
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ملخص الرسالة

الغرض من هذه الرسالة هو تحسين أداء شكل جديد من مصدر أيونات البنج ذو المحيط البارد وذلك لاستخدامه في التطبيقات المختلفة.

تم عمل عدة مناولة لوصول إلى الأبعاد المثلى للمصدر الأيوني ذو الاستخراج المحوري. حيث يمكن استخراج تيار عالي من الحزمة الأيونية في اتجاه عمودي على منطقة التفريغ.

ويتكون الشكل الجديد من مصدر أيونات البنج من مصعد مسطح يحاسي طوله بساعي 4 مم، وقطره يساوي 12 مم، وله نهاية على شكل مخروط طوله يساوي 15 مم، قطره العلوي يساوي 22 مم، وقطره السفلي يساوي 12 مم. مهبطان متحركان من مادة المولودنيم ومثبتين داخل عزل من مادة البرسيكس وموضوعان على بعد مماثل عن نهاية المصعد الأسطواني. قطب الأبعاد النحاسي ذو سمك يساوي 2 مم، وفتحة مركزية بأقطار مختلفة ووضع في منتصف المصعد وذلك لخروج الحزمة الأيونية. وقد تم عزل السطح الداخلي لقطب الأبعاد بمادة البرسيكس ما عدا مساحة قطرها يساوي 5 مم وذلك لتركيز التفريغ الكهربائي في هذه المساحة. كما تم وضع وعاء فارادي علي مسافات مختلفة من فتحة قطب الأبعاد وذلك لتجميع الحزمة الأيونية الخارجية من المصدر الأيوني.

تم إدخال غازات التشغيل إلى المصدر الأيوني من خلال فتحة في المصعد قطرها يساوي 2 مم بواسطة صمام إبرة والذي وضع بين أسطوانة الغاز والمصدر الأيوني.

تم تعين المسافة المثلى بين المصعد والمهبطان، قطر المساحة الغير مغطاة لقطب الأبعاد، قطر الفتحة المركزية لقطب الأبعاد، المسافة بين قطب الأبعاد ووعاء فارادي وذلك باستخدام غاز الأرجون. وقد وجد أن الأبعاد المثلى للمصدر الأيوني يساوي 6 مم، 5 مم، 2.5 مم، 1 مم على الترتيب حيث تفريغ كهربائي مستمر وتيار عالي من الحزمة الأيونية عند تيار تفريغ قليل يمكن الحصول عليه.

تم قياس خصائص التفريغ الكهربائي، خصائص الحزمة الأيونية وكمية المصدر الأيوني عند شروط تشغيل مختلفة وضغط مختلفة باستخدام غاز الأرجون.

كما تم قياس خصائص المصدر الأيوني عند شروط التشغيل المثلي وضغط مختلفة باستخدام غازي الأرجون والنيتروجين. وتم تعدين تأثير الجهد السالب المطبق على وعاء فارادي على تيار الحزمة الأيونية الخارجية من المصدر الأيوني.
تم تعيين تأثير مجال مغناطيسي دائم علي خصائص التفريع للمصدر الأيوني. حيث تم استخدام مجال مغناطيسي من مادي سمار يم - كوبولت. وقد وجد أن المسافة المثلى بين المصعد والمغناطيس الدائم تساوي 1.5 سم والتي تم الحصول عليها من تجارب عديدة.

تم قياس طاقة الجسيمات الثقيلة المشحونة لبلازما داخل المصدر الأيوني باستخدام نظام محل الطاقة. حيث تم تعيين الأيونات المتأخرة بوضع جهد موجب علي شبكة التأخير، ومن النتائج العملية تم الحصول علي توزيع الطاقة.

تم تعيين كفاءة المصدر الأيوني باستخدام غاز النتريوجين والأرجون. كما تم حساب البر فنوس للمصدر الأيوني من النتائج العملية باستخدام غازي النتريوجين والأرجون. وأيضا تم تعيين زمن التشغيل لهذا المصدر الأيوني بتعريف عينة من المولودينم لأيونات غاز الأرجون. كما تم مقارنة النتائج العملية بالحسابات النظرية.

وأخيرا تم دراسة تأثير الحزمة الأيونية الخارجية للمصدر الأيوني في التطبيقات، وخاصة علي عينات من البوليمر PM 355. وقد وجد أنه بزيادة زمن تعرض العينات للحزمة الأيونية تزيد القدرة على الامتصاص وبالتالي يحدث عبر للربط داخل البوليمر.
إنشاء مصدر للحزمة الأيونية وتطبيقاته

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