11 Positive-Ion Sources

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11.1 Introduction

This chapter is intended to center around the two main groups of ion sources of recent electrostatic ion accelerators. Sorted by placement of ion sources, the first typical group is the ion sources of single-ended machines and the terminal ion sources of tandem accelerators, and the second group is the positive-ion sources applied at the low-energy side of tandem accelerators. In all cases, so-called pressurized accelerators are considered.

In the first group, one of the following ion sources is used: an RF, a Penning or a duoplasmatron ion source. These are listed by their decreasing occurrence. Their lifetime expectancy must be over 400–1000 hours to keep maintenance down to an acceptable level. In simple solutions, the ion source is directly connected to the acceleration tube entrance, and they are matched by a single lens. In more sophisticated systems there are many lenses, a mass separator or a Wien filter between them.

In the second group, the positive-ion sources are placed in the open air, generally close to ground potential, or sometimes there is some acceleration potential between the ion source and ground. A tandem accelerator requires a negative-ion beam at its low-energy tube entrance, which can be produced directly from a negative-ion source, or indirectly using one of the former positive-ion sources, followed by a so-called charge exchanger. Either the direct or the indirect method is used; the source lifetime is less important than that of terminal sources. Tandem accelerators are often built with a double injection entrance containing an RF source or a duoplasmatron for producing light ions, and a cesium-sputtering ion source for heavier and metal ions. The advantage of this group of accelerators is obvious when a wider scale of ion species is desired.

The aim of this chapter is to survey the topic of positive-ion sources, basically in the context of single-ended accelerators. The negative-ion sources are discussed in Chap. 12. If particular positive-ion sources (e.g. sources used in low-energy, high-intensity implanters) or the more detailed theory and practice of ion sources are the main interest, readers are directed to [1–3].

11.2 The Plasma Physics of Ion Sources

The ion source is basically a plasma generator. As it is based on plasma physics, its operation can be described by basic plasma parameters and by fundamental processes.

11.2.1 Basic Plasma Parameters

Plasma Density and Degree of Ionization

The plasma state is the fourth state of matter. A plasma consists of ions, electrons and neutrals. Their number per unit volume can be given by the plasma neutral density (n_0), plasma electron density (n_e) and plasma ion density (n_i). In a plasma containing multiply charged ions, every ion component has its own ion density. In ion sources, the plasma is quasi-neutral; that is,

$$e \sum_i i n_i \cong e n_e \tag{11.1}$$

The index i goes through the different charge states ($i = 1, 2, 3, \ldots Z$). This equation is not valid close to the plasma wall. Many times the plasma density simply means the density of the plasma electrons. Typical values in ion sources are 10^{10}–$10^{16}\,\mathrm{cm}^{-3}$.

Plasma Temperature

Generally, the concept of "temperature" is valid only for Maxwellian energy distributions, which cover many kinds of plasmas but not all. In spite of this, quite often the "plasma temperature" is used also for the plasmas of ion sources, which are not in equilibrium. The ion temperatures T_i (of i-times ionized ions) and the electron temperature T_e are not necessarily equal, and in the presence of a magnetic field the temperatures parallel and perpendicular to the field may be different, especially for the electrons. In such a case the term "plasma temperature" has no meaning. It is usual to define the plasma temperature in electron volts (eV), where 1 eV corresponds to 11 600 K. Typical plasma electron and ion temperatures are several eV. In some plasmas (e.g. ECR discharges), however, $T_{e(perpendicular)}$ can be over 1 keV.

Ionization Cross Section, Mean Free Path

In the plasma, several interactions can happen in collisions: excitation, ionization, recombination and charge exchange. For every interaction, a corresponding cross section (σ) and mean free path (λ) can be defined. If one of the plasma components has a density n, then

$$\lambda = \frac{1}{n\sigma} \tag{11.2}$$

Ion Lifetime and Confinement Time

The average time between the birth and the loss of an ion with a given charge is called the lifetime. Typically τ_i is about 1 ms for highly-charged-ion sources. The lifetime in confinement sources is frequently called the confinement time. The relation between τ_i and λ is

$$\tau_i = \frac{\lambda}{v} = \frac{1}{n\sigma v} \tag{11.3}$$

where v is the (Maxwell–Boltzmann average) velocity of the ions.

Plasma Frequency

Any local deviations of the plasma particles from charge neutrality generate a force that redirects them into their original states. This process results in oscillation of the plasma particles at a frequency which is called the plasma frequency, and for the charged components of the plasma, ω_{pe} and ω_{pi} are the electron plasma frequency and ion plasma frequency, respectively. The electron plasma frequency is

$$\omega_{pe}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e} \tag{11.4}$$

where ε_0 is the permittivity of free space, e and m_e are the charge and mass of the electron, and n_e is the density of electrons. A similar expression can be written for ω_{pi} by substitution of qe, m_i and n_i in place of e, m_e and n_e. Here q is the ion charge state.

Cyclotron Frequency

A charged particle with velocity v rotates in a magnetic field. The frequency of this rotation is the cyclotron frequency. For electrons, the electron cyclotron frequency is

$$\omega_{ce} = \frac{e}{m} B \tag{11.5}$$

where e is the elementary charge, B is the magnetic induction and m is the electron mass. $f_{ce} = \omega_{ce}/2\pi = 28B$ (GHz), if B is in tesla. In the case of oscillating ions, this frequency is called the ion cyclotron frequency ω_{ci}, and is given by

$$\omega_{ci} = \frac{q_i e}{m_i} B \tag{11.6}$$

where q_i is the ion charge state and m_i is the ion mass. Since the magnetic field strength applied in ion sources is usually $B = 0.1$–$1\,\mathrm{T}$, the cyclotron frequency for electrons is 1–30 GHz, and 100 kHz – 10 MHz for ions.

Plasma Sheath and Debye Length

The charged plasma particles exert an influence on each other within a certain distance through the plasma. This distance is called the shielding distance. Particles at a greater distance than the shielding distance have no influence on the "screened" volume of the other particles. The metal wall of the plasma container or the imposed electric field similarly has no effect inside that "screened" volume, where charge neutrality is preserved. The boundary layer covering the "screened" volume is called the plasma sheath. This layer is not charge-neutral. Mainly the electrons, because of their higher mobility, follow a distribution such that it establishes an equilibrium transition layer between the plasma and its boundary. The Debye length λ_D is $1/e$ times the width of this transition layer. It is given by

$$\lambda_D = C\sqrt{\frac{T_e}{n_e}} \tag{11.7}$$

where $C = e^{-1}\sqrt{\varepsilon_0 k}$, e is the electron charge and k is the Boltzmann constant.

If a floating electrode is inserted into the plasma, it will assume a potential, called the floating potential, which is negative with respect to the plasma by about 3 to 4 times kT_e. When a high voltage is applied to this electrode, the sheath will be thicker than that of the former, unbiased case. The thickness of the high-voltage sheath is

$$d_{HV\,sheath} = \sqrt{\frac{V_{HV}}{kT_e}} \tag{11.8}$$

The formation of a plasma boundary has outstanding importance in the optimization of the shaping of the extracted ion beam.

11.2.2 Fundamental Processes in the Plasma

Electron Impact Ionization

The most fundamental ionization process in ion sources is the ionization of atoms or ions carried out by energetic electrons. For maximum electron impact ionization, the electron temperature T_e (or the electron energy given by $E_e = kT_e$) should be several times larger than the ionization potential of the subshell of the atom to be ionized. In most cases the resulting ions are singly charged owing to the low energy of the colliding electrons.

Multiple ionization can take place when the electrons have an energy at least equal to the nth ionization potential. The ion charge state increases successively, starting from $i = 0$ or from some other lowest charge state, in the following ways:

– step-by-step single ionization

$$A^{i+} + e^- \rightarrow A^{(i+1)+} + 2e^- \tag{11.9}$$

– single ionization by excitation in the following processes

$$\begin{aligned} A^{i+} + e^- &\rightarrow (A^{i+})^* + e^- \\ (A^{i+})^* &\rightarrow A^{(i+1)+} + e^- \end{aligned} \tag{11.10}$$

where the asterisk means an excited state.

Ion Impact Ionization

Similarly to electron impact ionization, collision of energetic ions with neutral atoms can cause ionization. The ionization cross section is a maximum when the fast ion has a velocity equal to that of the orbital electron to be removed. This is satisfied if the ion energy is higher by the ion–electron mass ratio than the energy of the electron. The contribution of this phenomenon to the whole ionization process is rather low because of low probability of production of such energetic ions.

Surface Ionization

The phenomenon where atoms are ionized by contact with a hot metal surface is called surface ionization or contact ionization. It needs a residence time of the particles long enough (10^{-5} to 10^{-3} s) for them to come into thermal equilibrium with the hot surface. Low-work-function alkali and alkaline earth metals (Li, Na, K, Rb, Cs, Ca, Sr, Ba, etc.) in contact with refractory-metal hot plates (Ta, W, Re, Ir, Pt, etc.) are useful for ion production. For example, P_i of Cs on W at 1500 K is 0.99, and this process is used in Cs-ionizers producing Cs^+ ions for sputtering the cathodes of so-called Cs-sputtering negative-ion sources. The ionization can be increased significantly by covering the hot plate with the aluminosilicate of the alkali metal.

Field Ionization

Sharp points at high voltage can emit either electrons or ions from solids or liquids. About 10^8 V/cm electric field strength is generated at the tip of a needle or a capillary, and this very high field ionizes streaming gas, vapor or molten metal at the tip.

Ion Loss Processes

In the plasma, the opposite of the ionization process also takes place: ions can be recombined by electron capture or charge exchange. Furthermore, some of the ions and electrons exit the plasma volume and are lost at the wall of the chamber. All these processes have their own cross sections, similarly to the ionization [4].

11.3 Ion Sources

11.3.1 Low-Pressure Gas Discharges with DC Current

In the ion sources discussed in this section, ions are produced directly from a low-pressure source gas, or indirectly by bombarding ionizable substances with charged components of that gas. Depending on the ion current intensity I, this low-pressure, self-maintained gas discharge is called a Townsend discharge when $I < 10^{-6}$ A, a glow discharge when $I = 10^{-4}$ to 10^{-1} A, and an arc discharge when $I > 10^{-1}$ A, if the cross section of the discharge tube is supposed to be a few cm^2.

Townsend Discharge

The space charge effect can be ignored because of the low current intensity. The region between the electrodes is dark, except for a slight glow appearing close to the anode.

The value of the ignition voltage U_{ign} required for the ignition of the discharge depends on the properties and pressure p of the gas, and on the electrode distance d. It has been shown that the curve of U_{ign} has a minimum in the range of $pd = 13$ to 1300 Pa cm. This minimum varies with the type of gas. The curves representing $U_{ign} = f(pd)$ are called Paschen curves. U_{ign} is also influenced by the cathode material through its secondary-electron emission coefficient, and is dramatically decreased when a heated cathode is used.

Glow Discharge

This can be experienced in the discharge volume at low gas pressures ($p = 13$ to 130 Pa) if the discharge current varies in the range $I = 10^{-4}$ to 10^{-1} A. The space charge cannot be ignored, as it causes significant distortion of the electric field.

Arc Discharge

This takes place at discharge currents $I > 10^{-1}$ A in the low-pressure discharge area.

The electron gas and the ions produced in collisions form a quasi-neutral system, which is the plasma of the arc discharge. This plasma covers almost the total volume of the discharge vessel, except for a thin layer along the vessel wall and the anode and cathode fall regions. This layer is not quasi-neutral, and its thickness along the wall is about $2\lambda_D$.

11.3.2 High-Frequency Gas Discharges

A gas discharge generated by a high-frequency field differs in many features from a DC gas discharge. Under the influence of a high-frequency field with a periodically alternating magnitude and direction, a certain amount of charged particles is unable to escape from the discharge space. As a consequence, the loss of ions and electrons is less important.

The secondary processes at the cathode surface also have smaller importance, and thus the high-frequency field can be coupled to the plasma region from both inside and outside the discharge vessel, and electrodes emerging into the plasma can be screened from ion and electron bombardment in order to avoid their sputtering and erosion. This results in a longer lifetime compared with that of DC ion sources.

The type of discharge is determined by the gas pressure p and, as a consequence, the free mean path λ and the collision frequency ν of the electrons; the frequency f of the alternating field; the electrode spacing d; and the radius r of the discharge space.

Alternating-Electric-Field or Linear High-Frequency Discharge

The discharge tube is made of an insulating material, and a high-frequency electric field is formed by two electrodes. The electrodes are located internally or externally, one at each end of the tube. Under the influence of the electric field, the free electrons oscillate at the frequency of the field. If the electrons do not lose any energy during their oscillation (very low pressure), no energy is transferred to them from the field. If they lose energy and the energy transferred is sufficient to cause inelastic collisions, the gas molecules in the tube can dissociate. The dissociation initiates excitation and ionization of atoms and molecules.

The value of the ignition voltage U_{ign} depends on the gas species, on the frequency of the alternating field and on the gas pressure. U_{ign} is shown as a function of these parameters in Figs. 11.1 and 11.2.

Alternating-Magnetic-Field or Ring High-Frequency Discharge

The discharge tube is placed in a solenoid driven by high-frequency power. In practice, the solenoid is the inductance of a resonant circuit in a high-frequency power oscillator. The solenoid induces circular currents, and at its ends an axial electric field as well, in the discharge tube.

Let the applied alternating magnetic field be $H = H_0 \sin \omega t$. The condition for ignition of a ring discharge must satisfy the following equation:

$$rH_0 \frac{e}{m_e} = \frac{2eU_i/m_e + (\omega\lambda_e)^2}{\omega\lambda_e} \tag{11.11}$$

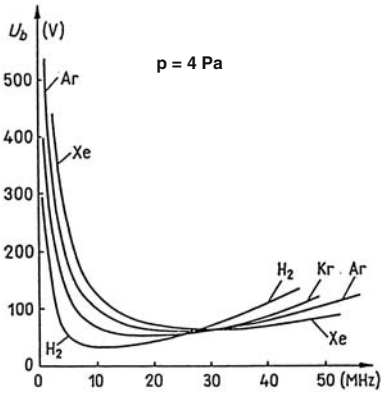

Fig. 11.1. U_{ign} as a function of high-frequency alternating field for different gases

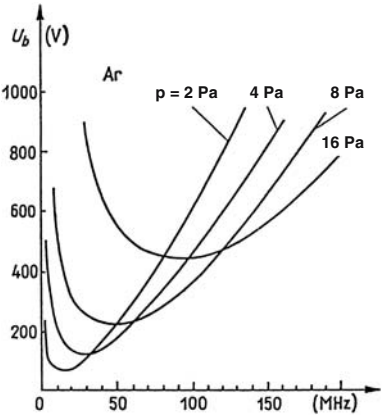

Fig. 11.2. U_{ign} as a function of high-frequency alternating field in argon for different pressures

where H_0 is the maximum value of the magnetic field; e, m_e and λ_e are the charge, mass and mean free path of an electron; and U_i is the ionization potential. The minimum value of H_0 can be calculated from (11.11), and varies with the field frequency ω and with the gas pressure p, since λ_e is proportional to $1/p$. With an axial electric field, the minimum value of H_0 can diminish.

Influence of Static Magnetic Field on Gas Discharges

In DC discharges, a magnetic field forces the electrons to circulate in a helical orbit at a Larmor frequency $f_H = eH/(2\pi mc)$, and thus the number of collisions and ionized particles increases, similarly to that what happens in the case of increased pressure. So, in the presence of a magnetic field, a given discharge intensity can be maintained at a lower pressure than without it.

In linear high-frequency discharges under the influence of a transverse magnetic field, a resonance-type increase can be observed in the electron energies, in the discharge current and in the power consumption at the frequency $\omega_H = 2\pi f_H = \omega$. Here and in the following paragraphs, ω_H is the Larmor frequency of the same arrangement in a DC electric field with an applied static magnetic field, and ω is the frequency of the alternating field.

A magnetic field parallel to the direction of the electric field applied to a linear discharge also increases the charged-particle current density, and the increase is higher when the magnetic field is inhomogeneous (see Fig. 11.3).

In a ring high-frequency discharge, its intensity increases substantially both in a transverse and in a longitudinal static magnetic field, and it is accompanied by a resonance-type power consumption and luminosity of the plasma in the $p = 0.1$ to 5 Pa pressure range. The dependence of the power

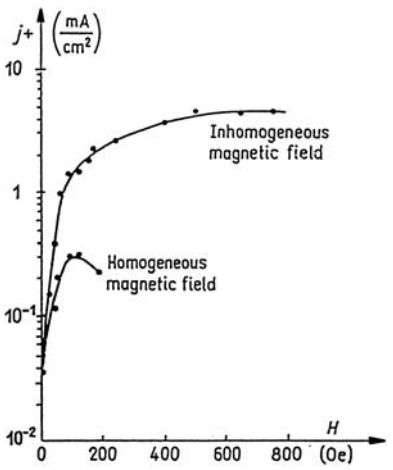

Fig. 11.3. Ion current density vs. homogeneous or inhomogeneous magnetic field

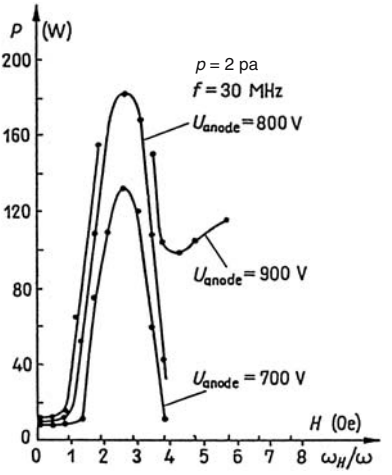

Fig. 11.4. Dependence of power consumption of ring discharge on applied transverse magnetic field and on ω_H/ω at different values of anode potential

consumption of a ring discharge on the applied transverse magnetic field and on ω_H/ω is shown (Fig. 11.4) at different values of the anode potential. The resonance in a transverse magnetic field has been observed at $\omega_H = 1.5\omega - 3\omega$, while in a longitudinal magnetic field it has been observed at $\omega_H = 3\omega - 6\omega$.

11.3.3 Traditional Ion Sources

Duoplasmatron

This is an arc discharge ion source using both a magnetic and an electric field to govern the plasma, from which the source derives its name. This source is used typically for ionizing gaseous materials. It was developed by Von Ardenne [5]. The plasma is composed of two regions inside the source: a lower-density cathode plasma maintained at a relatively high pressure (10 Pa) between the cathode and the IE, and a very high-density ($\sim 10^{14}/\mathrm{cm}^3$) plasma at a much lower pressure (about 0.1 Pa) between the IE and the anode. The cathode plasma is compressed by a double sheath into the IE channel as in the case of the unoplasmatron and then further compressed by a more or less axial magnetic field, applied between the IE and the anode. In Fig. 11.5 a power-saving low-intensity positive duoplasmatron ion source is shown; this is advised for operation in the high-voltage terminal of a single-ended electrostatic accelerator.

Like typical duoplasmatrons, this arrangement also contains a hot cathode, and an intermediate electrode (IE) and an anode plate, both made of

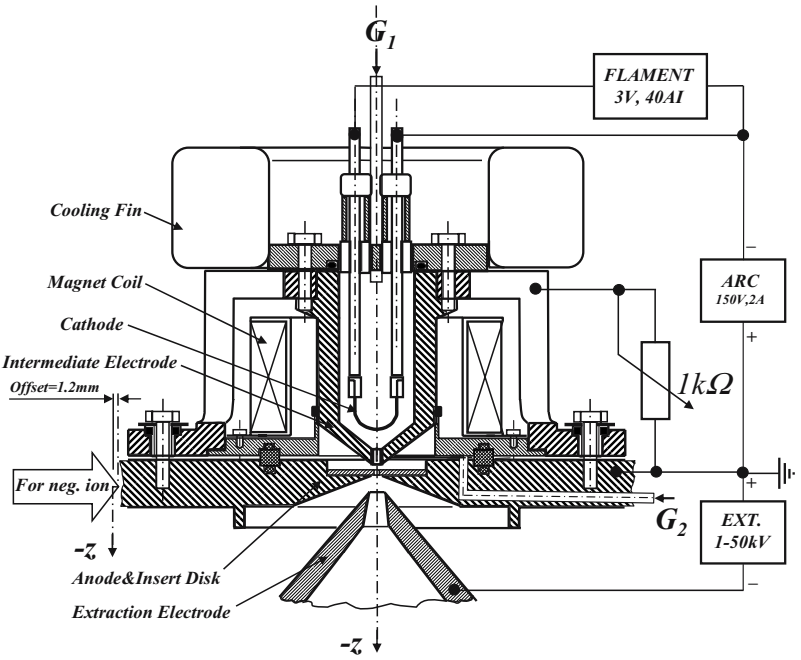

Fig. 11.5. Duoplasmatron ion source: scheme and circuitry

soft-iron in order to concentrate the magnetic flux between them along the z-axis, where the maximum magnetic induction is in the range of 0.1–0.3 T.

The cathode is heated and electrons are produced by thermionic emission. These electrons are accelerated by the electric field through the intermediate electrode toward the anode. As the IE potential is between that of the cathode and the anode, it produces some electrostatic focusing, which is accompanied by a strong magnetic focusing of the electron beam due to the magnetic flux between the IE and the anode.

When a gas (or vapor) is admitted (through G_1 in Fig. 11.5) into the cathode–IE region, the atoms or molecules enter the electron beam, and either they are ionized directly by the colliding electrons, or the molecules are dissociated and then ionized. The ion yield is dependent upon the electron beam intensity and the gas pressure. If the gas pressure is too low, the probability of collision with electrons is low. If the pressure is too high, the electron energy is insufficient and the mean free path λ is too short to cause molecular dissociation and ionization. In the case of normal operating conditions, the ions and electrons form a plasma ball in the cathode–IE region covered by an electrostatic double layer on the cathode side of the ball. The ions run toward the cathode and the electrons in the opposite direction. The number of electrons emitted from the cathode is increased by the impact of accelerated ions with the cathode.

The ion temperature in the plasma ball increases and, partly owing to compression by the double layer and partly owing to the pressure difference between the cathode–IE and IE–anode regions, the plasma material flows through the hole in the IE with these energetic ions into the IE–anode region. In this region, the strong magnetic field, regulated by the excitation of the magnet coil, causes magnetic plasma constriction. It also serves as a magnetic mirror, trapping the electrons, thus increasing their lifetime in the ionization process. For this reason, the ion temperature increases further. In the hot plasma, any neutral particle will be ionized before it escapes from the confinement area, and the plasma will go through the anode aperture. This hot plasma consists of positive ions of atomic, molecular and even triatomic particles, and, furthermore, of negative ions and electrons. Either positive or negative particles can be extracted by an extraction electrode connected to a power supply with an adequate value and polarity referred to the anode.

If this so-called extraction voltage power supply has a negative polarity with respect to the anode (as seen in Fig. 11.5), the positive ions are extracted, and the negative ones and the electrons are repelled backward. With reverse polarity, negative ions can be extracted, but the beam intensity is about two orders of magnitude lower compared with positive-ion-beam extraction. It is worth mentioning that in this case electrons can be excluded from the resulting beam by off-axis extraction (the axis of the ion source is shifted with respect to that of the extraction electrode, as shown in Fig. 11.5), or by a magnetic filter.

The resistor between the IE and the anode helps the easy ignition of the discharge, which always requires a higher voltage than does maintaining the discharge. After ignition, the IE potential gets closer to the cathode potential, to a greater or lesser extent depending on the electron current emitted from the cathode. The electron current is correctly adjusted when the potential of the IE is half or slightly above half of the arc voltage. If the IE voltage is significantly larger than this value (that is, the electron emission is below optimum), the ions (especially the heavier ones) sputter the cathode. Too high an electron emission results in high-frequency instability of the discharge.

The high-intensity arc discharge strongly erodes the IE and the anode apertures. As a consequence, the apertures will be distorted or completely closed. The lifetime of the apertures can be prolonged if sputtering-resistant liners and insert disks are applied in the IE and the anode. These are often made of graphite, tungsten, a copper–tungsten alloy, titanium or molybdenum. Basically, the lifetime of these elements and the cathode lifetime determine the source lifetime, which is around 1000 hours or above. The beam current – if everything is optimized – is roughly proportional to the area of the insert apertures, which are frequently made as an increasing series in 0.15 to 0.2 mm inner-diameter steps. Obviously, a smaller aperture results in lower gas consumption.

As the duoplasmatron is normally used only for producing light ions, the cathode lifetime is about 1000 hours. In the rare cases, when heavier ions or ions of corrosive gases are desired, these gases are admitted through the inlet G_2 of the ion source in order to avoid cathode deterioration; meanwhile, the primary discharge is maintained by the injection of a light gas. In a better solution for producing ions from heavier or corrosive gases, the ion source has a so-called expansion cup (see later), and the second gas inlet is connected to that cup.

The cathode material in H sources is typically oxide-coated tantalum, tungsten band or wire. More rarely, barium-oxide-coated platinum mesh is used. LaB_6 cathodes have, essentially, longer lifetimes, especially in high-current duoplasmatrons. If the cathode is heated directly with AC current, the filament voltage must be low (and as a consequence, the current is high), otherwise this would cause arc voltage modulation and thus excessive energy spread. In the normal case, the energy spread of the duoplasmatron ion source is about 10 to 15 eV, mainly due to the oscillation of ions in the negative anode fall of the discharge voltage distribution characteristics. A new cathode and a vented discharge chamber need a long time for outgassing, because pumping down is only possible through the small apertures of the IE and the anode. The pumping time is significantly diminished when a bypass valve is applied.

The duoplasmatron is able to produce ion currents of up to 200 mA in DC mode and a few A in pulsed mode, limited by the heat dissipation in the anode due to the high arc power, so these high-intensity ion sources are cooled by liquid coolants. In the high-voltage terminal of a single-ended machine, less than 1 mA ion current is sufficient, and the power consumption and dissipation are much lower. The magnet coil, the anode, the IE and the filament leads can be cooled by means of the high-pressure insulating gas of the machine streaming around the cooling fins. In Fig. 11.5, only the cooling fin of the IE is illustrated. A larger, ring-contoured fin is fitted to the anode, and two semicylinder-contoured fins are applied to the copper bars holding the cathode.

It is important to note that the gas pressure relations can be maintained only when the pressure on the extraction side is not higher than 10^{-3} to 10^{-4} Pa. This needs efficient pumping from the main vacuum system of single-ended machines. In the case of tandem accelerators, a directly connected high-vacuum pump is regularly applied to the ion source. The gas consumption of the source introduced is lower than 15 cm^3/h under normal operation. Sometimes cm^3/h NTP, that is, cm^3/h at normal temperature and pressure, is mentioned. The standard (or normal) temperature is 273.15 K and the standard pressure is 101 325 Pa.

A further possibility for decreasing the power consumption of low-current ion sources is to replace the hot cathode by a cold, hollow cathode and the magnet coil with a permanent magnet, as announced in [6]. In this source, a permanent magnet is also used for magnetic confinement of the hollow

cathode. Initiation of the discharge requires a similar gas pressure to that which a hot-cathode source does, but the discharge voltage is 600 to 700 V, which is significantly higher than that of a hot-cathode system. After establishment, a lower value of the arc discharge can be maintained, and the gas pressure can be reduced to any desired value between 10 and 10^{-2} Pa. The power consumption remains below 62 W at 0.5 to 3.0 mA beam currents of Ar.

As the plasma density near the anode aperture is very high, many sources are equipped with a plasma expansion cup. In this cup the plasma expands and thus cools, providing an increased area over which the beam can be extracted and transported through the ion-optical system. The expansion cup is a cylindrically shaped electrode in mechanical and electrical contact with the anode at the extraction side. In some cases, the anode is made of copper and the magnetic flux immersed in the expansion cup also affects the plasma formation. The plasma sheath, the effect of the magnetic field and double-layer formation, and the extraction of the ion beam from the source plasma without and with usage of an expansion cup are discussed, and the theoretical expectations are compared with the experimental results in a brief article [7].

Duoplasmatrons are typically used for production of singly charged gaseous ions. Their ionization efficiency is about 90%, and the proton yield is 30 to 70%. Multiply charged ions can be generated by increasing the arc discharge voltage, but in DC operation this results in extremely high dissipated power. In order to avoid this, the ion source is operated in pulsed mode. Another possible way to get multiply charged ions is the optimization of the magnetic field for the maximum product $n_e\tau_i$ in DC mode. Unfortunately, the optimum magnetic field is very close to the value where instability appears. Solids, practically, are not ionized by duoplasmatrons. For this purpose, the duoPIGatron has been developed.

DuoPIGatron Ion Source

This source is a modified duoplasmatron, with a so-called reflector electrode added to it following the anode. The reflector electrode is connected to cathode potential or close to it, and the electrons coming through the anode aperture are reflected between the IE and the reflector electrode, as in PIG discharges (see later), hence the name of the source. It was constructed by Demirkhanov [8]. The oscillation of the electrons between the IE and the reflector electrode further increases their ionization efficiency, and a higher amount of gaseous ions can be produced than with the duoplasmatron. If the reflector electrode is covered by the metal of interest and a heavy gas is used as the source gas, intensive sputtering occurs on this metal surface, producing the desired metal ion. The metal ion yield increases with the magnetic field and with the arc voltage at which the gas pressure can be lowered. Singly or, in certain cases, multiply charged ions of all the elements from H to U–except

Be, K, As, Br, Rb, Ru, Rh, Te, I, Cs, Re, Os, Tl and Th–produced by the source have been reported in [9].

Penning Ion Sources

These are often called PIG ion sources, from F. M. Penning, the inventor of the Penning or Philips ionization vacuum gauge. Penning ion sources are arc-discharge ion sources with electrons oscillating between a hot and a cold cathode or between two cold cathodes through a hollow anode, in a magnetic field. The cathode and the anticathode are at the same negative potential with respect to the anode, of radius R, as shown in Fig. 11.6. All of these elements are placed on a common axis, which is nearly parallel to the magnetic field of a solenoid or permanent magnet. The electrons attracted by the anode and affected by the magnetic field move along an expanding helical orbit with a radius of r_e. For a given geometry, the maximum of r_e depends on the magnitudes of the electric and magnetic fields E and B, as well as on the direction of the electron velocity relative to the magnetic field. At a sufficiently high B, the maximum value of r_e becomes lower than R, and thus the electrons cross the hollow volume of the anode and proceed toward the opposite cathode. The negative potential of that cathode redirects the electrons – which have lost a certain amount of their energy in elastic and inelastic collisions – without impact with its surface. The whole process is repeated between the cathodes until the electrons have lost their energy in successive collisions with molecules to a level at which they strike the anode. The resulting ions are transported to both cathodes and release secondary electrons from them. Secondary electrons then oscillate like primary electrons and take part in the ionization process. Hence a dense plasma is formed. Owing to electron collisions with atoms and molecules, electrons diffuse through the magnetic field to the anode, where they are collected to return to the power supply, but there is another diffusion mechanism as well. The sum of the two currents gives the current of the discharge power supply.

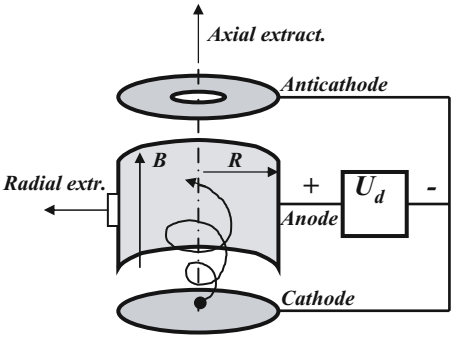

Fig. 11.6. Operation principle of the Penning ion source

The arc discharge will be self-maintained if each ion produced by a primary electron emitted from the cathode strikes the cathode and ejects at least one new electron. The secondary-electron emission coefficient δ expresses the ratio of ejected electrons n_{es} to the primary particles n_p incident on the surface: $\delta = n_{es}/n_p$. The secondary-emission coefficient of the cathode surface depends on the material of the cathode, the quality of the cathode surface and the ion energy. As a consequence, the ignition voltage U_{ign} and the formation of the self-maintained discharge are influenced by the proper choice of the cathode material and the cathode surface. By coating the cathode surface with an oxide layer, the secondary-emission coefficient can be increased. The materials used for low and higher ignition voltages U_{ign} are listed in Table 11.1. The oxide-coated materials gradually lose the oxide layer because of sputtering, and approach the U_{ign} of the pure metal. Their lifetime can be extended by 2 to 10% O_2 admixed with the ionized gas. An oxide layer deteriorated by cathode sputtering can be regenerated on the cathode surface if the discharge is operated for 10 to 30 minutes with oxygen gas. The aspects of choosing the cold-cathode material besides U_{ign} are the cathode lifetime, the value of the discharge voltage (which is lower than U_{ign}) and the discharge stability. The best material is uranium, which ensures a stable discharge at low anode voltage and with low sputtering. In most cases, titanium is also suitable. Tantalum requires a relatively low discharge voltage, and it has a very low level of sputtering. It can be used in both low- and high-current

Table 11.1. Materials used for low and higher ignition voltage U_{ign} [10]

Material	U_{ign} (V)	Sputtering Loss in H_2 (mg/Ah)
Materials suitable for low U_{ign}		
Al + O_2	350	<29
Mg + O_2	400	
Be + O_2	300	
Fe	400–500	68
U	500–800	<30
Ti	800–1000	<30
Materials suitable for higher U_{ign}		
Ni	3600	65
Zn	3600	340
Al	3500	29
Cu–Zn alloy	2800	
Monel	2800	
Cu	2300	300
C	2300	262
W	2100	57
Mo	1800	56
Ta	1700	16

sources. If the cold cathodes are intentionally heated up by the arc discharge, tantalum is a better choice.

The ions can be extracted axially along the discharge axis through one of the cathodes, or radially, where the direction of the extraction is perpendicular to the discharge axis, often through a slit aperture. Generally, PIG ion sources with axial extraction are used for higher ion currents, and radial- or transverse-extraction sources for lower ion currents, but both arrangements are suitable for both modes of operation. Radial extraction is mainly applied for cyclotrons, where the cyclotron magnet itself provides the magnetic field of the ion source.

Penning sources can be operated in two main pressure regimes: in the low-pressure regime from 10^{-6} to 1 Pa, and in the high-pressure regime from 0.1 to 100 Pa. The second regime is also divided into two types: cold-cathode PIG sources are operated with arc voltages above 1 kV at an arc power less than 1 kW, and hot-cathode PIG sources are operated with arc voltages below 1 kV. In a cold-cathode PIG operated at 1 kW or higher arc power, thermal electron emission starts. If high arc current is desired from a cold-cathode PIG (e.g. multiply charged ions are required), it must be operated in pulsed mode to limit the thermal power.

In the first heated-cathode PIG ion sources, one of the cathodes was a filament and the other cathode was floating. These sources have been used up to now in cyclotrons. In modern, high-current, heated-cathode PIG ion sources, electrons emitted from a filament, accelerated to 1 keV, are used to heat the rear side of the cathode. In this way, the cathode temperature can be controlled independently of the ion current from the plasma to the cathode, and optimum arc conditions can be adjusted. The anticathode is cold. Heated-cathode PIG ion sources deliver the highest currents of multiply charged ions of all the conventional ion sources [11]. With this type of PIG source at 1100 V and 13 A arc power, 4.9 mA Xe^{10+} and 0.01 mA Xe^{15+} ions were produced by a Ta cathode.

In single-ended machines, power consumption and vacuum load must be kept at a minimum, and the heated-cathode PIG ion source described above cannot be used. E. Heinicke, and later H. Baumann and K. Bethge, developed a PIG ion source with axial extraction suitable for these machines. The cold-cathode PIG ion source illustrated in Fig. 11.7 contains almost all of the advancements they carried out. The upper and lower cathode pole pieces, with a pot-shape and upper disk-like cores, are shown as soft-iron parts composing a soft magnetic yoke, excited by the magnet coil. The magnet coil liner, made of stainless steel, is the sidewall of the discharge chamber. The anode (molybdenum or stainless steel) is fixed in a rimmed stainless steel tube, insulated from the iron yoke by a ring-shaped insulator outside of the discharge area. The stabilized high-voltage power supplies used as discharge power supplies may have a very low internal impedance, which makes the discharge unstable. To avoid this, a resistance R is applied.

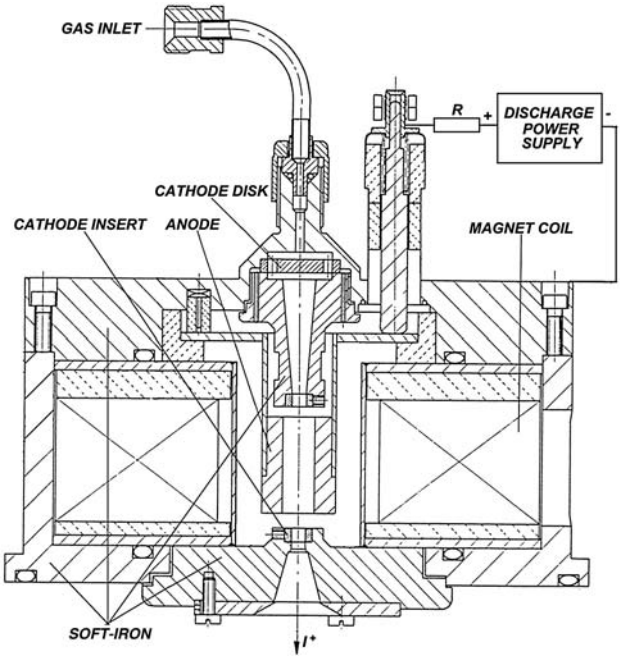

Fig. 11.7. A compact PIG ion source applicable to a single-ended electrostatic accelerator

A version of this source was published in [12]. That source – unlike the source in Fig. 11.7 – did not contain a closed magnetic yoke and thus consumed too much excitation power, and as a consequence, liquid cooling was required. The inner bore of the magnet coil bobbin was insulated from the end pieces holding the cathodes, and directly supported the anode, so discharge was possible only inside the molybdenum anode cylinder. The bore diameter of the anode was 8 mm and the length of it was 23 mm. The cathode separation was 27 mm. The volume of the discharge chamber is reduced greatly with this design, resulting in less outgassing. The cathode disks were made of tantalum. The source was operated in the high-discharge-voltage, low-discharge-current and low-pressure mode, with the following operating data: $U_d = 1$ to 6 kV; $I_d = 1$ to 20 mA; $H = 0.05$ to 0.15 T; $p \approx 0.1$ Pa. In the experiments carried out with the source, maximum total beam currents of 1 and 4 mA have been extracted with an average discharge power of about 20 W/mA. The following conclusions have been drawn about the optimal operating conditions for the production of multiply charged ions: the optimal gas flow rate and the optimal magnetic field strength have to be increased in proportion to the discharge voltage. The optimal gas flow decreases with increasing mass of the source gas, whereas the optimal magnetic field does not depend on it. This second result suggests that the magnetically guided

electron motion determines the ionization state in the discharge. This relates mainly to the primary and oscillating electrons. The ion currents for various ion species and charge states, with source operating data, are presented in Table 11.2. $I_{i,tot}$ includes the molecular-ion components as well. The energy spread of the extracted total ion beam was measured by the retarding-field method, and 60 to 80 eV was found for Ar. The gas consumption decreases with increasing mass number of the operating gas. The intensity of the ion current $I_{i,tot}$ can be expressed as $I_{i,tot} = CU_d/m_i^{1/2}$, and for the value of C, about 2.5 has been derived from the experiments.

Table 11.2. Ion currents for various ion species, and source operating data

Ion	Gas	U_d	I_d	H	P	$I_{i,tot}$	$I_i^{\zeta+}$ (μA)								
		(kV)	(mA)	(T)	(W)	(mA)	1+	2+	3+	4+	5+	6+	7+	8+	9+
He	He	3.2	15	0.07	48	3.1	3080	17							
Ne	Ne	4.5	8.4	0.076	37.8	2.7	2420	169	10	0.34					
Ar	Ar	5	6.5	0.086	32.5	2		1740	175	21	4	0.6	0.085	0.006	
Kr	Kr	4.2	4.4	0.076	18.5	1.3	1030	185	60	15	5	1.5	0.34		
Xe	Xe	5.4	3.7	0.076	20	1.25	840	230	117	40	12	4.3	1.8	1	0.42
Cl	HCl	4.2	4.8	0.097	20.1	1.6	1500	36	3.5	0.64	0.18				
Br	Br_2	4.5	8	0.188	36	1	900	108	19	3.1					
I	HI	4	2.1	0.094	8.4	0.68	600	72	22	10	2.4	0.44			
O	O_2	4	19	0.094	76	2.3	700	23	0.26	0.003					
S	H_2S	4	5.4	0.094	21.6	1.85	300	21	1.5	0.28	0.02				
Se	H_2Se	4.7	4.9	0.104	20.2	1.65	300	27	6	2.4					
N	N_2	4	11.5	0.094	46	2.6	500	16	0.22	0.003					
P	PH_3	4.1	6	0.099	24.6	1.9	150	7.7	0.82	0.12					
As	AsH_3	4.6	5.3	0.104	24.4	1.75	200	19	5	1.9		0.1			
B	BF_3	4	4.9	0.094	19.6	1.6	80	1.36	0.06						

This source was designed for producing gaseous ions. By replacing the Ta cathode with uranium, U ions were created by sputtering in the low-voltage, high-current discharge mode at 1.5 kV discharge voltage and 23 mA discharge current, in a 0.1 T field, with beam currents from 70 to 0.1 μA and charge states from 1+ to 8+. It is worth noting that this technique can be used in general if the desired metal, applied as a cathode, has a sufficiently high melting point for sputtering, though the metallic-ion yield is not so high.

The extraction-side cathode of the source had an opening which had not been eroded after a long operating period. The opposite cathode, originally a plain disk without a hole, showed a crater-shaped erosion profile with the diameter of the extraction-side cathode opening. This means that the plasma is concentrated along the source axis, and that the cathode lifetime, about 60 hours when Ar ions were produced, depends mainly on the wear of the plain disk cathode. Elsewhere it is found that the cathode is worn out when the diameter of the crater is equal to its depth. The other main limiting factor of PIG ion sources the short-circuiting of the anode–cathode gap by evaporated metal layers covering the insulator surfaces, or by peeled-off ones from the anode bore surface. Both problems can be decreased by placing the

cathode disk in a field-free space in the polepiece. In the drift space formed by the cavity, the ion beam expands under the influence of its own space-charge forces from the initial 3 mm to a maximum of 7 mm before it hits the cathode disk. In this way, the sputtering current density on the cathode surface decreases by about a factor of 5, and the cathode lifetime increases in the same ratio to more than 500 hours. A further advantage of this cathode is that 90% of the sputtered cathode material is deposited inside the drift cavity. The new cathode design, published in [13], is shown as the upper cathode of the PIG source in Fig. 11.7.

The PIG ion source announced in the earlier section has been developed to produce multiply charged ions. Further developments of the source for production of ions from solids also have been published by the same authors in [14]. The basic construction of the source is very similar to that of Fig. 11.7. The power requirement of the magnet coil is only 25 W owing to the closed magnetic circuit of the soft-iron yoke, so this source runs with air cooling. Consequently, this ion source is ideal for application in single-ended machines and in high-voltage terminals of tandem accelerators as well. The three modes of operation are the following:

- *Ion production from gases.* In the basic mode, the operation data are the same as in the case of the previous source when it produced multiply charged gaseous ions. It is important to note that from the monatomic gas Ar, ions are produced with ion current intensities of 1400, 130, 17 and 2.5 μA for the 1+, 2+ 3+ and 4+ charge states, respectively, whereas from the multiatomic gas BF_3, only ion currents of 80 μA B^+ and 1.3 μA B^{2+} are available. This means that it is better to use a solid element such as B for ion production instead of a gaseous compound.
- *Ion production from solids by evaporation.* At temperatures below 1000°C, about 30 elements have a vapor pressure in the range 10^{-2} to 10^{-1} Pa. These elements can be ionized in the high-voltage, low-current mode with the source. For this purpose the anode is replaced by a heated one, which serves as an evaporation furnace as well. The anode is fixed in the anode support by spikes to avoid thermal loss. Therefore, a power of 60 W is sufficient to heat the anode up to 700°C. In this way, the vapor of the solid can be ionized in a supporting discharge gas such as an inert gas. From P in Ne, 100 μA 1+ and 5.5 μA 2+ can be produced, from Mg in Ar, 270 μA 1+, 56 μA 2+ and 1 μA 3+ can be produced.
- *Ion production from solids by sputtering.* The evaporation method is not applicable for high-melting-point solids such as Ta and W. These elements can be applied as a cathode disk or a cathode-covering material, and sputtered by positive ions of a rare-gas discharge, and thus the required material moves to the plasma. In a PIG source such as that shown in Fig. 11.7, optimized for gaseous ions, the un-ionized part of the sputtered material is deposited on the wall of the discharge chamber and the anode. The authors have designed a modified anode and upper-cathode arrangement for

replacement of the anode and upper cathode of Fig. 11.7. In their design, the upper cathode piece is elongated and the cathode disk is placed at the tip of it, similarly to a traditional PIG cathode. In this way, the cathode separation and the discharge space between the cathodes decreased to a length of about 6 mm. The modified anode is only a thin aperture between the cathodes, supported by the old anode holder. As a result, the sputtered material moves from cathode to cathode and a small amount of it is deposited on the anode. The modified source is operated in the high-current, low-voltage discharge mode ($I_d = 40$ to 200 mA, $U_d = 0.5$ to 0.7 kV) with argon as the support gas, and Al, Ti, Fe, Cr, Ni, Cu, Mo, Ta and W singly or multiply charged ions were produced in the ion current intensity range of 20 to 200 μA.

The value of the emittance has been given only for the high-voltage, low-current operating mode. In this mode, the emittance of the source is 0.2 to 1 cm mrad $\mathrm{MeV}^{1/2}$, depending on the ion mass and beam intensity.

Investigations in [11] have pointed out that ions can be produced with sufficient efficiency and acceptable stability anywhere within a wide magnetic-field range. Owing to this recognition, many laboratories developed PIG ion sources where the magnet coils were replaced with ceramic or rare-earth permanent magnets. The PIG sources published in [15] fitted directly into the place of an HVEC RF ion source, so the ion optics were kept identical in the KN 4000 single-ended machine. One of the sources contains six ferrite ceramic magnet rings. At 0.1 T field, 1.7 kV discharge voltage, 2 to 10 mA discharge current and 4×10^{-2} Pa gas pressure, 30 nA He^{2+} current could be extracted through a cathode aperture with a diameter of 0.7 mm, which was an order of magnitude higher than the current extracted from the original RF ion source. It is impossible to pump down the residual gases through such a small aperture, and it is difficult to control the gas flow to the discharge volume, so two additional holes parallel to the extraction hole were added to increase the pumping cross section.

Both positive and negative ions can be extracted from PIG ion sources. A so-called "pocket" PIG ion source was reported recently [16] with a 3 cm diameter × 3 cm SmCo magnet and LaB_6 cathodes (with a 3 mm hole on the extraction-side cathode). The gap between the cathodes and the anode is very small compared with their diameter, similarly to the sputter mode version of the modified PIG explained previously. The source runs in the high-current, low-voltage mode at 80 mA discharge current. It can produce positive and negative ions from gaseous and solid materials with a beam current of the order of 1 mA. At 10 kV extraction voltage, about 2 mA O^- and F^- ion beams can be extracted.

RF Ion Sources

The name comes from "radio frequency", and they are often called HF, i.e. high-frequency, ion sources, because their plasma is generated by the radio frequency field produced by a high-frequency oscillator or generator. In typical cases, an RF oscillator built with one or two transmitter electron valves provides the RF power. The frequency of the oscillator is at a constant value between 15 and 125 MHz, and the RF output power of it is 50 to 400 W.

The source is called an inductively coupled RF ion source, and the RF power is connected inductively to the discharge volume if the discharge tube is placed into a solenoid of a few turns in the resonant circuit of the oscillator. If the source is capacitively coupled, points on the previous solenoid or on a twin-lead resonant transmission line having a sufficiently high RF voltage are connected to two clips placed around the discharge volume. The discharge volume is covered by a Pyrex or quartz tube.

For the extraction of the ions, two basic methods are accepted. The first one was proposed by Thonemann et al. [17] and consists of a positive W electrode – called the probe – at the closed end of the discharge tube, and a grounded aperture made of metal at the opposite end. In the second, probeless bottle version – developed by Bayly and Ward [18] and improved by Harrison [19] and others – one of the ends of the discharge tube is closed, and both electrodes are placed at the other end concentrically to each other and to the tube. Either type of extraction can be applied with either coupling. Thus, the ion sources are called the Thonemann-type RF source with capacitive coupling, the Harrison-type RF source with capacitive coupling or with inductive coupling, etc. The different versions of RF ion sources are illustrated below by two typical examples.

RF Ion Source with Thonemann-Type Extraction and Capacitive Coupling

The RF source designed by Moak, Reese and Good [20] and shown in Fig. 11.8 is a good representative of this kind of source. The discharge tube is made of Pyrex glass with a diameter of 25 mm and a length of 220 mm. The probe or anode electrode of the source is formed by a threaded Al cylinder cemented in a vacuum-tight way in the discharge tube, cooled by an Al fin. The extracting electrode, made of Al, has a 6.3 mm long extracting canal with a diameter of 1.6 mm, and it is covered by a precisely fitted quartz tube. The oscillator, with a frequency of 100 MHz and an output power of 60 W, is connected to two clips, causing a linear high-frequency discharge in the Pyrex tube. An axial, inhomogeneous, static magnetic field is excited by the magnet coil and compresses the plasma around the axis. At 6 cm^3/h gas consumption, a 1.2 mA total ion current could be extracted with a +5 kV probe voltage. The power consumption of the magnet coil is significant, and thus it is often replaced by a permanent-magnet ring.

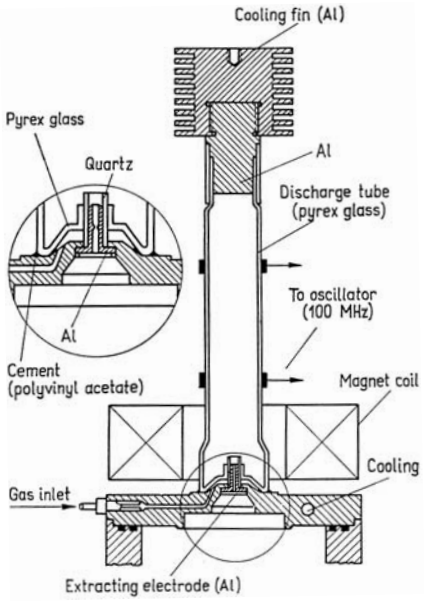

Fig. 11.8. The RF source designed by Moak, Reese and Good [20]

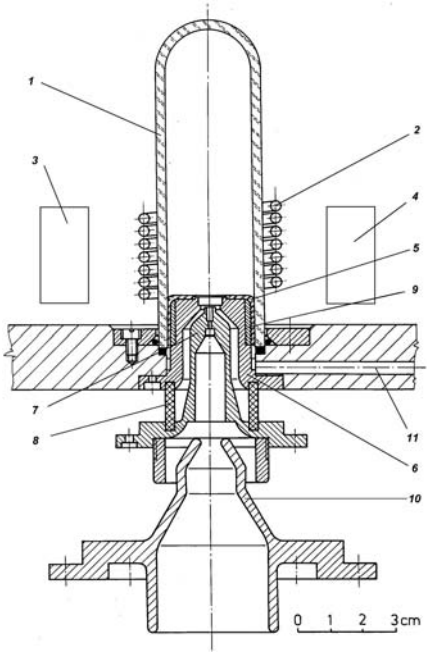

Fig. 11.9. RF ion source with a further-developed Bayly and Ward-type extraction and with inductive coupling

The RF ion source with a further-developed Bayly and Ward-type extraction and with inductive coupling shown in Fig. 11.9 represents the other group of sources [21]. In the quartz bottle (1), a high-frequency ring discharge is induced by the solenoid (2), driven with 47 MHz, 100 W RF power. A transverse magnetic field of about 5×10^{-3} T is produced between the permanent magnets (3) and (4), which greatly increases the intensity of the discharge. The potential of the anode (6) is fixed to the baseplate of the source, and the extraction electrode (7) is kept at a negative potential relative to it, which is variable between 0 and 10 kV. The quartz cup (5) shades a significant part of the anode metal surface from the plasma sheath in order to decrease recombination at it. The axial error in the manufacturing of elements (6) and (7) and in the assembly of them on the baseplate and on the accelerator tube axis is less then ± 0.03 mm, and the source is applied without any steering element at the entrance of the accelerator tube. Therefore, the deflection effect of the magnets (3) and (4) is eliminated by screening the extraction canal with a soft-iron ring (8). The source, when operated in a single-ended machine, causes a considerable gas load at the entrance of the acceleration tube, pumped only at the opposite end of the tube. The Teflon insulating ring (9) allows one to get the source gas into the tube entrance area through

the extraction bore only, and thus diminishes the vacuum load on the acceleration tube. The source gas is fed through the gas inlet (11). The proton yield of the source is about 80% if carefully optimized, and strongly depends on the clarity of the quartz discharge tube. This phenomenon can be explained by increasing recombination on the inner tube surface. Flushing of the tube with hydrofluoric acid of 4% concentration and rinsing with distilled water are required to maintain maximum proton yield.

This source is identified as ATOMKIa, with a stepped extraction canal diameter, and as ATOMKIb, with a constant diameter, in Table 11.3, where its main parameters are compared with the parameters of HVEC Model C-SO-173 (identified as SO173) and ORTEC-IONEX Model 320 (identified as IEX320) ion sources provided with Thonemann-type extraction, indicated by "Th." "B–W" means the Bayly and Ward type of extraction. The subscript H means that the measurements were carried out with hydrogen. The emittances were measured at the focused beam energies and currents. The ion currents and gas consumption vs. extraction canal diameter and length are shown in Table 11.4.

The lifetime of the source is limited by erosion due to sputtering of the extraction tip, and by contamination of the discharge tube with condensed evaporated cathode materials. The condensed layer first only reduces the proton yield, and then thicker pieces of it peel off and block the extraction canal. Both symptoms increase with increasing extracted ion current and ion mass.

Table 11.3. Ion currents for various ion sources, and source operating data

			Canal Dimensions		Geom. Divergence	Max.		Life-	Emittance Measured at			
			Length	Diam.	Angle	i_H	Q_H	Time	$V_{Extr.}$	$V_{Focused}$	i_H	ϵ
	Type	Ref.	mm	mm	deg.	mA	cm^3/h	h	keV	keV	mA	cm rad $\sqrt{eV}$
Th.	SO173	[22]		2.1		2	10	700				
Th.	IEX320	[23]	12.5	1.2	±5.5							
Th.	IEX320	[23]	12.5	1.6	±7	0.75	4	175	2.7	35	0.5	0.35
B–W	ATOMKIa	[21]	3.0*	1.4	±10	0.25	4	600	3	10	0.1	0.43
			4.0*	0.7								
B–W	ATOMKIb	[21]	7.0	1.5	±12	3.0	11	120	3	10	0.12	0.48

* Total length = 3.0+4.0

Table 11.4. Measured data for H gas consumption and beam intensity vs. extraction canal dimensions

Diameter (mm)		Length (mm)		Gas Consumption	Ion Current
Canal Entrance	Canal	Canal Entrance	Canal	cm^3/h	mA
1.50	0.80	4	3	4	0.22
1.50	0.90	4	3	4.7	0.24
1.50	1.00	4	3	5.5	0.45
1.50	1.20	4	3	7.8	1.60
1.50	1.40	4	3	11	2.40
	1.60		7	14	3.00
	1.80		7	28	3.90

RF sources are used typically for producing light ions such as H^+, H_2^+, D^+ and He^+, but with lower intensities, heavier ions and doubly charged ions also can be extracted, as was investigated in [24] with the RF source shown in Fig. 11.9. Not only singly charged, but also molecular and doubly charged ions were produced with the application of helium, nitrogen, neon, carbon dioxide, methane and Freon-12 at moderate or low intensities. The usual frequency (47.5 MHz) of the source had been increased to 78 MHz and the gas flow minimized in order to get ions from $^4He^{2+}$ to $^{15}N^{2+}$ with usable intensities. The analysis of $^4He^{2+}$ ions is impossible with the usual magnetic and electrostatic separators since the e/m value and velocity of $^4He^{2+}$ are almost the same as those of the always present H_2^+. To avoid this difficulty, use of the ^{3}He isotope has been proposed to test the efficiency of He^{2+} production [25].

11.3.4 Increased Demands

All the conventional positive-ion sources discussed up to this point are usable in single-ended machines and in terminal sources in the HV terminal of tandem accelerators, if they are designed so that their overall power and gas consumption are rather low, and they are vacuum-tight against the insulating-gas pressure. All of them can also be applied as positive or negative sources for ion injection into tandem accelerators. In these latter applications, the vacuum pumping difficulties associated with terminal sources, pressure resistance, high power consumption, the necessity for intensive cooling and shorter lifetime are not limiting factors. Still, to some extent, they are dedicated to a given purpose.

Production of ion beams with sufficient beam quality for nuclear microprobe applications is a big challenge nowadays. It is also well known that the beam quality of the ion source determines that of the accelerator. The beam quality available at some laboratories around the world was mapped by Szymanski and Jamieson [26]. Participant laboratories were asked to report their own microprobe parameters to the authors. Then they determined the beam brightness parameter B (a figure of merit of the charged-particle beam, announced elsewhere) from the formula

$$B = \frac{i}{A_o A_a E/d^2} \tag{11.12}$$

where i is the beam current on the specimen (pA), A_o is the area of the object collimator (μm^2), A_a is the area of the aperture collimator (mm^2), d is the distance between the collimators (mm) and E is the beam energy (MeV). B is obtained in the units $pA/(\mu m^2\,mrad^2\,MeV)$. The normal brightness and beam configuration in different laboratories are shown in Table 11.5, where the normal brightness B_n is the approximate brightness measured at a divergence of nominally 0.07 mrad for the object collimator, which has the highest brightness for the system.

Table 11.5. Normal brightness and beam configuration in different laboratories

Group	$B_n \simeq B$ at 0.07 mrad	Beam	Energy (MeV)	Ion Source	Accelerator
Debrecen	0.3	H^+	2	RF	Single-ended e.a.[a]
Faure	1.5	H^+	3	Duoplasmatron	HV KN tandem e.a.
Heidelberg	0.05	H^+	2.2	Penning	3 MV e.a.
JAERI	0.7	He^+	2	RF	NHV[b] NV3000B single-ended
Leipzig	20	H^+	2.25	RF	HVEE Singletron
Lund-1	2.0	H^+	2.7	RF	NEC 3UH
Lund-2	7.0	H^+	2.55	RF	NEC 3UH
Melbourne	6.0	H_2^+	3	RF	NEC 5U
Melbourne	2.0	He^+	3	RF	NEC 5U
Melbourne	4.5	H^+	3	RF	NEC 5U
Oxford	0.6	H^+	3	Duoplasmatron	NEC 5SDH-2 tandem
Shanghai	0.25	H^+	3	RF	NEC 4UH
Singapore	30	H^+	2	RF	HVEC AN2500
Sydney	1.0	H^+	3	Duoplasmatron	General Ionex Tandetron

[a] e.a. = electrostatic accelerator
[b] NHV = Nissin High Voltage

The following conclusions were drawn. The paraxial rays of the beam are about an order of magnitude brighter than the surrounding ones. This distribution of brightness is very similar in different accelerator systems. It seems that it does not depend on the type of machine used to provide the beam. Both single-ended and tandem machines, with RF and duoplasmatron ion sources show the same effect. The article suggests that a Penning source, which is known as a medium-quality ion beam source, is rarely used here; the duoplasmatron is used more frequently. The RF ion source is the most preferred in this field. It was also concluded that an ECR source, with 5 to 10 times higher brightness, and a gas field ionization source, with orders of magnitude higher brightness, compared with that of the best RF sources, can be promising alternatives in the future.

11.3.5 "Exotic" Ion Sources

This pallet of ion sources is much more colorful than those described in the section that dealt with traditional sources (see e.g. in [3]). Because of limited space, only two kinds of them will be briefly described below; these sources are – or can be – applied in single-ended machines.

ECR Ion Sources

The family of microwave ion sources is composed of the true ECR sources and of those operated out of the ECR regime. From (11.5) the electrons gyrate around the magnetic-field lines at the cyclotron frequency $f_{ce} = \omega_{ce}/2\pi = 28B\,(\mathrm{GHz})$, if B is in tesla. The electron gyromotion is right-handed, and

thus axially propagating right-hand-polarized waves (at a frequency of f_{ce}) can couple power into the plasma via plasma electrons. By this resonant power transfer, the electrons of the plasma can be heated to very high energies (the electron temperature can reach 10 keV). The process is called electron cyclotron resonance heating (ECRH), and the plasma is called an ECR plasma. ECRH is only possible when the electron collision frequency $\nu < f_{ce}$, i.e., the pressure of the source gas is 10^{-4} to 10^{-3} Pa. The very high-energy plasma electrons produce very highly charged ions in the ECR plasma. Microwave power can be absorbed resonantly by the plasma if the electron plasma frequency (see (11.4)) $\omega_{pe} < \omega_{ce}$, otherwise it is reflected. The microwave frequency equal to the electron plasma frequency is called the cutoff or critical frequency. Using (11.4), a critical electron density ($n_{e,crit}$) can also be derived and is given by $n_{e,crit} = 1.25 \times 10^{10} f'^2\,(\mathrm{cm}^{-3})$, where f' is the microwave frequency in GHz. Though, apparently, ECR cannot be created above the critical electron density, under some conditions it can be formed with a density greater than the critical density. Such a plasma is called an overdense plasma, and is advantageous when a higher ion intensity is required, for example in ion sources.

In an ECR ion source, the ECR plasma is confined by axial mirror coils or magnets, and by radial permanent magnetic multipoles. The resulting magnetic field (magnetic bucket) has a relatively low field strength in the central region, and it gradually increases in any direction from the center to the chamber wall (B-minimum geometry). This results in an effective magnetic trap for the electrons, and the space charge of the electrons keeps the ions inside this magnetic trap. The microwave power is in the range between 10 and 1000 W. Up to 5 GHz frequency and 300 W power, it is coupled with a coaxial cable; above that, it is coupled with a tube transmission line to the discharge chamber. In some cases the ECR ion source contains two discharge regions. A high-pressure (0.1 Pa) primary plasma is created in the first chamber, and the charged particles (electrons and low-charge state ions) diffuse along the magnetic-field lines into the second, low-pressure (10^{-4} Pa) chamber. The ion temperature in ECR sources is very low (lower than 1 eV), because only the electrons are heated by the microwave power in the magnetic field. The extractable ion current increases linearly with the RF power.

An elaborated compact ECR ion source has been developed and installed into the high-voltage terminal of a single-ended CN-type 6 MV electrostatic accelerator [27]. The overall power consumption of the source is 900 W. It is pressure-resistant up to 6×10^5 Pa of SF_6. The maximum 200 W RF power is fed by eight pieces of 30 W GaAs FET amplifiers combined by a Wilkinson-combiner, and driven by a 5 GHz dielectric-resonator oscillator. High currents of lowly charged ions and reasonable currents of highly charged ions have been produced with the source, as shown in Table 11.6. The different charge states were separated with a Wien filter behind the source, and were tuned to the maximum. For lower charge states, the currents were intentionally limited to 20 µA.

Table 11.6. Analyzed currents of different charge states of the BECRIS ion source measured after acceleration and a 90° magnetic analyzer

Ions	Charge States, Currents in Electrical nA										
	1+	2+	3+	4+	5+	6+	7+	8+	9+	10+	11+
H_2	20000										
p	20000										
D_2	20000										
D	20000										
He	20000	10000									
N	20000	10000	2400	410	100	1.2					
O	20000	10000	400	620	130	26					
Ne	20000	10000	5000	1200	270	34	7.5				
Ar	20000	10000	3000	1450	1100	430	220	89	8	8	1.2
Xe	20000	20000	7000	4000	3000	2000	1000	1000	200	40	10

The value of the magnetic induction is 0.18 T in the ECR plane for 5 GHz. The ratio of the induction in the midplane to that in the ECR plane is 1.6, and thus the induction in the midplane is 0.11 T. For a mirror ratio of 3, a maximum magnetic induction of 0.32 T has been chosen. The radial hexapole field was realized by 36 pieces of FeNdB magnet sticks. The axial field was formed by three pairs of FeNdB rings. A schematic view of the BECRIS source is shown in Fig. 11.10.

Microwave power is often used for plasma generation at rather high pressures as well (0.1 to 1 Pa). At this pressure, the microwave-power coupling is

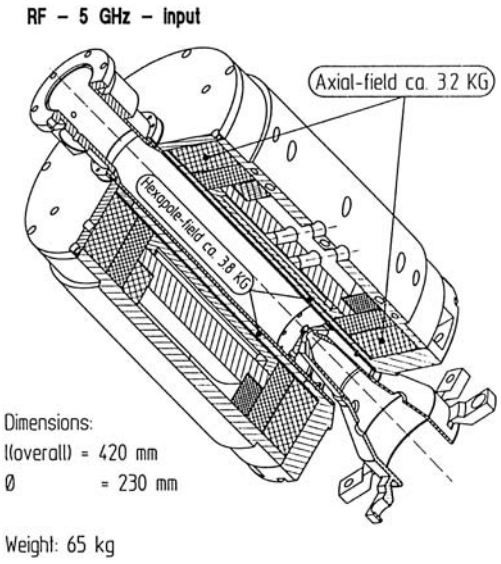

Fig. 11.10. Schematic view of the BECRIS source (Reprinted from [27], copyright 1994, with permission from Elsevier)

not resonant, since electron cyclotron motion is impossible ($\nu \gg f_{ce}$). This kind of discharge is called a high-pressure microwave discharge, and is accompanied by low-charge-state ion production. Some ion sources using 2.45 GHz microwave power produced by a magnetron high-frequency generator (made for household microwave ovens) often operate in this high-pressure discharge mode. Therefore, they are not ECR sources.

Field Ionization Sources

Field electron emission refers to the transfer of electrons from a metal surface into a vacuum under the influence of a very high electric field at the surface. Field ionization is the reverse of field emission and takes place when an atom or molecule is in an extremely high reversed-polarity electric field. The strong field polarizes the atom or molecule and lowers the potential barrier, which makes it possible for an electron to tunnel from the atom or molecule through the barrier into the metal. Using a reasonably high voltage, a very small radius of a tip is required to reach the desired 10^{-8} V/cm field strength. In practice, a needle having an apex end radius of about 100 nm and about 1 to 10 kV potential difference is applied. The small tip size results in a very high ion density, and therefore in high brightness. Examples of field ionization sources are the gas field ionization ion source (GFIS), and field-evaporation or liquid-metal ion sources (LMISs). In both ion sources, a needle or a capillary can be used. The gas pressure is 10^{-3} to 10^{-1} Pa. The needles are operated in ambient temperature or chilled to low temperatures.

Gas Field Ionization Sources (GFISs)

Figure 11.11 illustrates the two types of gas field ionization sources: (A) is the needle ionizer, and (B) is the capillary ionizer. A disadvantage of (A) is that, at high pressure, the un-ionized particles in the path of the extracted ion beam may act as scattering centers and thus degrade beam quality. An advantage is that the radius is much smaller than in the case of a capillary ionizer (a supertip). The version (B) reduces beam scattering.

A needle-type GFIS has been announced in [28]. The tip is made of tungsten or iridium. For optimum performance, the tip has to be kept at cryogenic temperatures of about 50 K. This so-called supertip has a diameter of 1 to 2 nm. The performance of the source is described in Table 11.7.

Liquid-Metal Ion Sources (LMISs)

In the needle-type version, the melted metal wets the tip. Metals with high melting points are applied in the form of low-melting-point alloys (eutectics). A Li^+ LMIS can be equipped with provision for remote wetting or rewetting of the needle. Such a source has been developed for the high-voltage terminal of an electrostatic accelerator for microprobe applications.

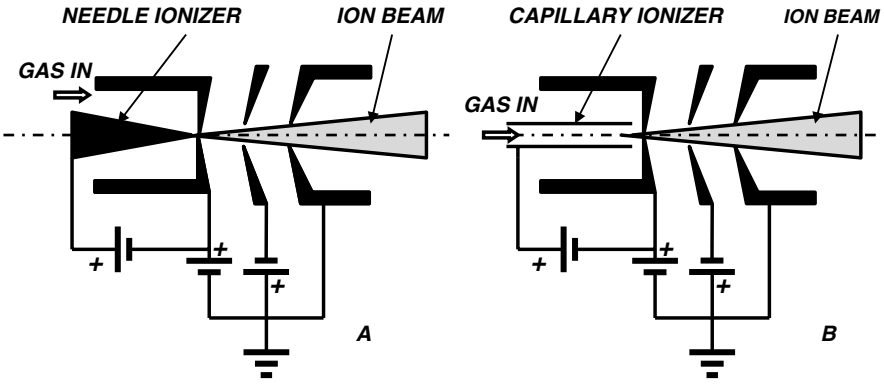

Fig. 11.11. The two types of gas field ionization sources: (**A**) is the needle ionizer, and (**B**) is the capillary ionizer

Table 11.7. The performance of the source

Particle species	e^-	H_2^+	He^+	Ne^+	O_2^+
Current (nA) into $\pm 0.5^\circ$	100	8	5	5	0.2[a]
Angular current density (μA/sr)	30	35	20	20	1
Energy spread (eV)	0.3	1	1	1	1[b]
Brightness (A/cm^2 sr)			10^{10}–10^{12} [c]		
Spectral brightness (A/cm^2 sr·eV)			10^{10} - 10^{12} [d]		

[a] Ir supertip, maximum particle current ≈ 1 nA O^+ (estimate)
[b] Ir supertip, extrapolated value
[c] Virtual source size $d_v \approx 0.1$ nm
[d] Energy spread $\Delta E \approx 1$ eV (FWHM)

References

1. A. T. Forrester: *Large Ion Beams: Fundamentals of Generation and Propagation* (Wiley, New York, 1988)
2. L. Vályi: *Atom and Ion Sources* (Akadémiai Kiadó, Budapest and Wiley, London, 1977)
3. B. Wolf: *Handbook of Ion Sources* (CRC Press, Boca Raton, 1995)
4. S. Biri, E. Koltay, A. Valek: Accelerators. In: *Handbook of Nuclear Chemistry*, Vol. 5, ed. by A. Vértes, S. Nagy, Z. Klencsár (Kluwer Academic, Dordrecht, 2003) pp. 76–78
5. M. Von Ardenne; *Tabellen der Elektronenphysik, Ionenphysik und Übermikroskopie* (VEB Deutscher Verlag Wissenschaften, Berlin, 1956)
6. A. Qayyum, S. Ahmad: Nucl. Instr. Meth B **94**, 597 (1994)
7. M. E. Abdelaziz, A. M. Ghander: IEEE Trans. Nucl. Sci. **NS-14**, 46 (1967)
8. R. A. Demirkhanov et al.: Proceedings of the First International Conference on High Energy Accelerator, Brookhaven National Laboratory Report 767, p. 218 (1962)
9. B. H. Wolf: Nucl. Instr. Meth. **139**, 13 (1976)
10. L. Vályi: *Atom and Ion Sources* (Akadémiai Kiadó, Budapest and Wiley, London, 1977) p. 184

11. B. Wolf: *Handbook of Ion Sources* (CRC Press, Boca Raton, 1995) p. 75
12. H. Baumann, K. Bethge: Nucl. Instr. Meth. **122**, 517 (1974)
13. H. Baumann, K. Bethge: Nucl. Instr. Meth. **171**, 621 (1980)
14. H. Baumann, K. Bethge: Nucl. Instr. Meth. **189**, 107 (1981)
15. E. Arai et al.: Nucl. Instr. Meth. B **59** 58 (1984)
16. Y. Jinxiang et al.: Proceedings of the Second Asian Particle Accelerator Conference, Beijing, p. 179 (2001)
17. P. C. Thonemann et al.: Proc. Phys. Soc. **61**, 483 (1948)
18. A. J. Bayly, A. G. Ward: Can. J. Res. **26A**, 69 (1948)
19. E. R. Harrison: J. Appl. Phys. **29**, 909 (1958)
20. C. D. Moak, H. Reese, Jr., W. M. Good: Nucleonics **9**, 21 (1951)
21. I. Kiss et al.: Revue Phys. Appl. **12**, 1481 (1977)
22. High Voltage Engineering (Europa) N. V.: Data sheet HV-A-6021
23. General Ionex Corporation: Ion source selection data
24. L. Bartha et al.: Nucl. Instr. Meth. A **287**, 156. (1990)
25. L. Vályi: *Atom and Ion Sources* (Akadémiai Kiadó, Budapest and Wiley, London, 1977) p. 249
26. R. Szymanski, D. N. Jamieson: Nucl. Instr. Meth. Phys. Res. B **130**, 80 (1997)
27. P. Arndt et al.: Nucl. Instr. Meth. B **89**, 14 (1994)
28. S. Kalbitzer, A. Knoblauch, Invited paper at the International Conference on Ion Sources, Taormina, Sicily (7–13 September 1997)