The ion source comprises a plasma source employing a microwave cavity which is excited in one of its modes of resonance and a static magnetic field adjusted to the electron cyclotron resonance, means for extracting the ions from the plasma and comprising an expansion cup pierced by an aperture which communicates with the cavity and ion-extraction electrodes brought to suitable potentials. The density of the plasma is of maximum value in the vicinity of the aperture and the static magnetic field is substantially zero in the vicinity of the extraction electrodes.
This invention relates to an ion source which makes use of a microwave resonant cavity and finds an application in the equipment of particle accelerators. Ion sources for accelerators must have a certain number of qualities and among these can be mentioned: flexibility of adjustments both in energy and in intensity, reproducibility of results, a long lifetime, the possibility of obtaining high ion densities.

Some of the qualities just mentioned are combined in ion sources of known types but there is no source at the present time which exhibits all these properties together. Thus, sources of the "duoplasmatron" type do not have a very long lifetime by reason of the presence of electrodes which are placed in the plasma, the lifetime of these electrodes — in particular the cathode — being limited as a result of the intense bombardment to which they are subjected.

High-frequency discharge sources operating between 20 and 100 Mc/sec avoid this major obstacle but the electron density of the plasma which is created remains of low value.

Plasma sources of the type designed for the use of a cavity which is resonant at microwave frequencies are also known. In some of these devices, the interaction between microwave and plasma is considerably increased by the application of a static magnetic field such that the conditions of electron cyclotron resonance are satisfied.

These plasma sources of the microwave cavity and cyclotron resonance type result in the creation of plasmas having high density but are not equipped with adequate ion-extraction means.

It is the precise object of the present invention to provide an ion source which employs on the one hand a plasma source having microwave-frequency excitation at cyclotron resonance and, on the other hand, extraction means of the type employed in the duoplasmatron but specially adapted to the plasma source employed. The ion source obtained in accordance with the invention accordingly has all the properties noted in the foregoing and thus represents a substantial technical improvement upon known sources.

More precisely, the invention is concerned with an ion source comprising:

a plasma source employing a microwave cavity which is excited according to one of its modes of resonance and a static magnetic field which is adjusted to the electron cyclotron resonance,

means for extracting the ions from said plasma, comprising an expansion cup pierced by an aperture which communicates with said cavity and ion-extraction electrodes which are brought to suitable potentials,

wherein the density of said plasma is of maximum value in the vicinity of said aperture, and wherein said static magnetic field is of substantially zero value in the vicinity of said extraction electrodes.

In a preferred embodiment, said static magnetic field assumes the value corresponding to cyclotron resonance only in the vicinity of said expansion cup aperture.

In another advantageous embodiment, a high static magnetic field gradient exists in the vicinity of said aperture.

Finally, in another alternative embodiment, the expansion cup has a low reluctance and constitutes a shield for the static magnetic field.

Further properties and advantages of the invention will become apparent from the following description of two exemplified embodiments which are given by way of explanation and not in any limiting sense, reference being made to the accompanying drawings, wherein:

- FIG. 1 is a diagram of a microwave circuit for the excitation of the ion source;
- FIG. 2 illustrates an ion source comprising a cylindrical cavity of revolution in which the plasma is confined within a dielectric cylinder;
- FIG. 3 shows the curves representing the relationship between the height and the radius of the cylindrical cavity in respect of different modes of excitation;
- FIG. 4 shows the lines of electric force and the distribution of the amplitude of the field for the TE_{111} and TE_{122} modes;
- FIG. 5 describes the TE_{011} and TE_{022} modes;
- FIG. 6 shows an alternative embodiment of the invention employing a truncated coaxial cavity which is excited in the TEM mode.

In FIG. 1, a microwave generator 1 excites an ion source 2 in accordance with the invention by means of a microwave circuit comprising a variable attenuator 3, a directional coupler 4, a matching element 5, a piston 6, a coaxial line 7 and an excitation antenna 9.

Pumping means (not illustrated) serve to create a vacuum within the cavity by means of the duct 21.

The operation of said microwave-frequency excitation circuit is as follows:

The generator 1 contains a microwave-frequency source such as a magnetron, for example, which produces the electromagnetic field. The attenuator 3 serves to vary the power of the wave which is injected into the system. The positions of the piston 6 and of the matching element 5 are adjusted so as to have the best possible matching of the cavity of the source 2. Mis-match is measured by means of the directional coupler 4 which draws-off a part of the wave reflected by the cavity towards the generator.

The ion source 2 is described in detail in FIG. 2 in one example of construction. In this figure, a cylinder 11 forms the side wall of the microwave cavity, said cavity being excited by a coaxial line 7 which is terminated by an antenna 9. A tuning screw 12 serves to vary the resonant frequencies of the cavity to a slight extent. An orifice 13 serves to inject the gas to be ionized into a leak-tight dielectric cylinder 14 which is coaxial with the cylinder 11. O-ring seals 15 and 16 ensure leak-tightness of the internal enclosure of the cylinder with respect to the remainder of the cylinder 11.

A cap 42 closes the cavity at the top end and an expansion cup 17 which is screwed onto the body of the cylinder 11 completes the resonant cavity 50. Said cup defines an expansion chamber 40 which communicates with the cylinder 14 through the aperture 41. Only one of the extraction electrodes is illustrated; this electrode 18 is negatively polarized with respect to the expansion cup 17 which can be connected to ground through the voltage source S. Coils 19 and 20 which are supplied with direct current produce a static magnetic field which is parallel to the axis of revolution of the cavity cylinder.
The operation of said device is as follows: The microwave-frequency excitation field propagates within the coaxial line 7 and excites the resonant cavity 50 by means of the antenna 9. The shape and position of said antenna are conducive to excitation of the cavity in a transverse electric mode — conventionally referred to below as the TE mode — characterized in that the electric field is in a transverse sectional plane of the cavity. The choice and nature of the resonance modes will be explained in detail hereinafter.

The gas to be ionized is injected through the opening 13; in accordance with this alternative embodiment of the invention, the gas penetrates into the interior of the dielectric cylinder 14 and is partially ionized under the action of the microwave electric field in conjunction with the static magnetic field, the amplitude of which is so adjusted that the cyclotron frequency is in the vicinity of the frequency of the microwave field. The coils 19 and 20 do not necessarily carry identical currents; in an advantageous variant, the coils carry very different currents such that the static magnetic field corresponds to the cyclotron resonance only in the lower zone of the cylinder 14 in the vicinity of the aperture 41 of the expansion cup 17. This aperture is thus located in the immediate proximity of the zone in which the plasma density is of maximum value, thereby promoting diffusion of said plasma within the expansion chamber.

Moreover and in accordance with a further property of the ion source of the invention, the static magnetic field produced by the coils 19 and 20 is very weak and even zero in the zone located near the extraction electrode 18 in order to prevent said field from disturbing the extraction of ions. This is possible by fabricating the cup 17 from a metal having low reluctance such as soft iron, for example, in order to form a magnetic shield. The sudden drop in amplitude of the static magnetic field across the aperture 41 therefore results in a high magnetic-field gradient at this point, thereby accelerating the plasma and facilitating the expansion of this latter within the chamber 40.

This expansion is accompanied by a reduction in density of the plasma and therefore by a reduction in the space charge which usually limits the ion currents which can be extracted. The electrode 18 which is brought to a highly negative potential makes it possible in accordance with a conventional method to effect a separation between the electrons and the ions. The shape and potential of said electrode are such that the ions are guided towards the enclosure formed by the tube 21, a high vacuum being maintained by means of pumps (not shown) within said enclosure.

The dimensions of the cylindrical cavity of revolution can be determined as follows:

In the alternative embodiment of FIG. 2, the magnetic field is parallel to the axis of the cavity. In order to derive benefit from the cyclotron resonance which is due to the presence of said field, it is necessary to ensure that the microwave electric field contained in the cavity has a component at right angles to the magnetic field. There is therefore every advantage to be gained by promoting the transverse-electric (TE) modes of resonance which are such that the electric field is contained in the transverse section plane. Strictly speaking, the existence of a component of the electric field which is parallel to the axis of the cavity as would be the case for a transverse-magnetic (TM) mode would not make the system inoperative but would only limit its efficiency. It is therefore endeavored to excite the cavity in a TE mode which will be designated more fully and with the conventional notations by $\text{TE}_{mn}$, wherein the indices $m$, $n$, $p$ refer to the field distribution along the usual cylindrical coordinates $\theta$, $r$, $z$, the $z$-axis being the axis of the cavity.

In order to avoid dimensions which are too large, the choice of indices $m$, $n$ and $p$ is limited to the low values 0, 1 or 2. For a given frequency of the generator, the height $h$ of the cavity is related to its radius $a$ by relationships which are conventional in the theory of microwave resonant cavities. In FIG. 3, these variations are shown in the case of four modes and at a frequency of 10 gigacycles. Each of these curves has a vertical asymptote which defines a minimum radius $a_{\text{min}}$. By choosing for the radius of the cavity a value in the vicinity of $a_{\text{min}}$, the upper modes will not be excited. In particular, by choosing for $a$ a value which is close to the lowest value of $a_{\text{min}}$ (namely that of the $\text{TE}_{111}$ mode which has a value of 8.8 mm at 10 gigacycles), it will be possible to excite the $\text{TE}_{111}$ mode alone and not the other modes.

The choice of the cavity excitation device is related to the mode of oscillation which is sought. As shown in FIG. 2, an antenna which is formed by the extension of the central conductor 9 of the coaxial 7 excites the modes in which the electric field has a component at right.

The dimensions of the cavity having been defined by means of the curves of FIG. 3, it can be useful to have a means for fine tuning of the resonant frequency of said cavity. In FIG. 2, this means is provided by the tuning screw 12 which is of metal. The depth of penetration of said screw within the cavity increases the resonant frequency of this latter and disturbs the lines of force of a mode of resonance. Different tuning means can be employed such as a cavity which makes use of a movable end-wall, for example. It is readily apparent that devices employing tuning means other than those of the screw type would not constitute any departure from the scope of this invention.

In FIGS. 4 and 5 there are shown a few examples of distribution of the electric field in the case of the modes of resonance which are most commonly employed. It is known that the amplitudes of the radial and tangential components of the electric field of the mode $\text{TE}_{mn}$ are products of sinusoidal function of the polar angle, of sinusoidal function of the $z$ coordinate, and of Bessel function of the radius vector. FIG. 4 describes two modes having an index $m = 1$. FIG. 4a gives the direction of the lines of electric force of the $\text{TE}_{11}$ mode and FIG. 4b gives those of the $\text{TE}_{12}$ mode. FIG. 4c gives the variations in relative amplitude of the electric fields of these modes for a polar angle $\phi = 0$ and FIG. 4d gives those for $\phi = \pi/2$.

FIG. 5 describes two modes having an index $m = 0$. Nullification of the first index eliminates variations according to the polar angle, with the result that the lines of electric force are concentric circles. Variations in the tangential component of the electric fields are shown in FIG. 5c.
The sinusoidal variations of the electric fields of these four modes along the z coordinate which is parallel to the axis are shown in FIG. 5d.

These different possible distributions result in different alternative forms of application of the invention:

in the event that the TE_{111} mode is chosen, the dielectric cylinder 14 of FIG. 2 necessarily intersects the lines of electric force. This cylinder will therefore be the cause of more or less substantial losses which will result in heating of the material. However, the choice of this mode does lead to advantages since it is apparent from the curves of FIG. 3 that, in this mode, the dimensions of the cavity and therefore the dimensions of the device are minimized.

The energy dissipated within the dielectric of the cylinder which limits the plasma can be considerably reduced if the radius of said cylinder is chosen so as to ensure that the cylinder walls occupy a zone of the cavity in which the amplitude of the electric field is small or even zero. In order that the amplitude of a component of the electric field should be zero at a point of the cavity other than a point located on the walls, it is necessary to ensure that the Bessel function which describes the variations in said amplitude as a function of the radius vector r is cancelled in respect of values other than the ordinary values r = 0 or r = a, if a designates the radius of the cavity. In accordance with a known property of Bessel functions, the index n must in that case be at least equal to 2.

The modes TE_{121} and TE_{021}, the distributions of which are illustrated in FIGS. 4c, 4d and 5c, possess this property. In the case of the TE_{121} mode, the field is zero at $\phi = 0$ and $r/a = 0.35$. At $\phi = \pi/2$, the field is zero when $r/a = 0.72$. A dielectric cylinder having a radius within the range of 0.35 to 0.72a will therefore be subjected to a low microwave-frequency field. So far as concerns the TE_{021} mode, the electric field is zero when $r/a = 0.55$, irrespective of the polar angle $\phi$. A thin dielectric cylinder having a radius $r = 0.55a$ and placed within a coaxial cavity resonant in the TE_{021} mode does therefore not produce any microwave-frequency loss. These arrangements also make it possible to derive benefit from the maximum value of electric field for the purpose of creating the plasma since this maximum value takes place within internal zones of the cylinder.

The use of modes of resonance having zones in which the field is either weak or zero within the cavity in order to minimize losses and heating of the cylinder is clearly not limited solely to the modes TE_{121} and TE_{021} which have been described. The use of any other mode having an index $n = 2$ would constitute only an alternative embodiment which would not depart from the scope of the invention.

In the foregoing description in connection with the operation of the device which is illustrated in FIGS. 1 and 2, no reference has been made to the disturbances produced as a result of the existence of a plasma within the interior of the cavity. The two main disturbances arise from drift of the resonant frequency of the cavity and from a drop in overvoltage of this latter. If f designates the no-load frequency of the cavity, creation of the plasma gives rise to a variation in the resonant frequency which becomes $f_p$. Similarly, if the initial overvoltage of the cavity were $Q_p$, the losses within the plasma cause said overvoltage to change to a value $Q_p'$. If the fixed frequency of the microwave-frequency generator has been chosen equal to f, the resonant-frequency drift of the cavity must be of lower value than the bandwidth of the resonance with plasma in order that the interaction between the wave derived from the generator and the plasma of the cavity should still be appreciable. This condition is therefore written:

$$|f - f_p| \leq f/20$$

For example, if the power absorption by the plasma is such that $Q_p = 1,000$, it will not be possible for the resonant frequency of the cavity to differ from that of the magnetron by an amount greater than 1.23 megacycles with $f = 2,459$ megacycles or 5 megacycles with $f = 10$ gigacycles.

The values of frequency drift and of overvoltage drop depend on the mode of resonance considered, on the diameter R of the dielectric cylinder 14, on the static magnetic field employed and on the electron density n of the plasma:

at low plasma densities ($n \approx 10^{14}$ m$^{-3}$ at 2,459 megacycles and at a pressure of 10$^{-2}$ Torr) and with a plasma having small dimensions ($R/a \approx 0.1$), the frequency drift is not significant; it can be considered that the cavity is resonant at the same frequency as in the case of operation on no load, that is to say at the frequency of the generator. The drift decreases in magnitude as $R/a$ is smaller and, for the same value of $R/a$, the drift is lower in the TE_{021} modes than in the TE_{121} modes. It is even possible to reduce said drift to zero by taking as a value of the static magnetic field the value of cyclotron resonance (875 Gauss at 2,459 megacycles), in which case the absorption of power by the plasma is of maximum value.

In the case of higher densities ($n \approx 10^{15}$ m$^{-3}$ at 2,459 megacycles) in a zero magnetic field, if it is desired to have an acceptable drift, it is also necessary to adopt small values of $R/a$ for the TE_{111} mode whereas, in the case of the TE_{021} mode, higher values may be adopted; in the case of a magnetic field in the vicinity of the value of resonance, the value of $R/a$ can be increased by maintaining an acceptable drift for the modes TE_{111} and TE_{021}.

In the case of high values of density ($n \approx 10^{18}$ m$^{-3}$ at 2,459 megacycles), the TE_{021} mode alone results in low values of drift in the vicinity of the cyclotron resonance.

Cylindrical cavities of revolution are not the only structures which permit the application of the invention. In another alternative embodiment of the invention which is illustrated in FIG. 6, the microwave cavity has a composite shape. The cavity is coaxial along the greater part of its length and the remaining portion is a cylinder of revolution.

In FIG. 6, a cylindrical cavity of revolution 50 is traversed along its axis by a magnetic metallic cylinder 23 which passes through the top wall 24; the cylinder 23 is pierced by a duct 25 and this latter communicates with a tube 26 which is brazed to the cylinder 23; the central conductor of the coaxial line 7 terminates in a coupling loop 27. An expansion cup 17 defines an expansion chamber 40 which communicates with the cavity 50 through an aperture 41; an extraction electrode 18 is negatively polarized by the source S. A sole plate 28 of soft iron, two columns 29 and 30 and an end-plate 31 constitute together with the magnetic metallic cylinder 23 a magnetic circuit for the static magnetic field.
produced by the two coils 32 and 33 which are mounted in parallel; O-ring seals 34 and 35 ensure leak-tightness of the cavity 30 and of the guide 21.

The operation of said device is as follows: the microwave-frequency excitation field penetrates into the cavity through the coaxial line 7. A current passes through the loop 27 and the resultant magnetic field excites the modes of resonance of the cavity which have a magnetic component at right angles to the plane of the loop. This coupling mode thus excites a transverse-electric-magnetic (TEM) mode. This mode of excitation is strictly the TEM mode only in that portion of the cavity in which this latter may be assimilated with a coaxial cavity; the gas to be ionized is injected via the tube 26 through the duct 25. This gas is subjected to the microwave-frequency field only as it emerges from the duct 25; it is also in this zone that the static magnetic field produced by the coils 32 and 33 enhances the microwave-plasma interaction as a result of the cyclotron resonance phenomenon, with the result that the aperture 41 is located very near the zone in which the plasma has the highest density. The shape of the magnetic circuit, and especially the presence of the soft iron coreplate 28 produces a high magnetic field gradient across the aperture 41 which promotes the extraction of the plasma as in the previous alternative embodiments. The plasma then diffuses within the expansion chamber 40 and the electrode 19 performs its ion-extracting function substantially without disturbance by the magnetic field.

In this alternative mode of application, the lines of electric force in the vicinity of the plasma-formation zone are less well defined than in the alternative embodiment which employs the cylindrical cavity. Although the microwave-frequency electric field is not perpendicular to the static magnetic field, the electron cyclotron resonance phenomenon which has been described still remains possible since the microwave-frequency electric field has a non-zero transverse component except possibly along the axis of the cavity. The electrons accordingly follow a helical path and no longer describe a plane curve.

The ion source in accordance with the invention can operate with a wide range of gases. Hydrogen in particular has led to the achievement of good results.

What we claim is:

1. An ion source comprising:
   a plasma source employing a microwave cavity which is excited according to one of its modes of resonance and a static magnetic field which is adjusted to the electron cyclotron resonance,

2. An ion source according to claim 1, wherein said static magnetic field assumes the value corresponding to cyclotron resonance only in the vicinity of said expansion cup aperture.

3. An ion source according to claim 1, wherein a high static magnetic field gradient exists in the vicinity of said aperture.

4. An ion source according to claim 3, wherein said expansion cup is fabricated from a metal having low reluctance and constitutes a magnetic shield for said static magnetic field.

5. An ion source according to claim 4, wherein said expansion cup is of soft iron.

6. An ion source according to claim 1, wherein said microwave cavity is a cylinder of revolution, said mode of resonance is transverse-electric, said static magnetic field is axial and wherein the plasma is confined within a leaktightly dielectric cylinder which is coaxial with said cavity and has a small radius compared with the radius of said cavity, said expansion cup being disposed in the axis of said dielectric cylinder.

7. An ion source according to claim 6, wherein the mode of resonance of the cavity is the TE_{111} mode.

8. An ion source according to claim 6, wherein said mode of resonance is a mode in which the electric field has zero amplitude in certain internal zones of the cavity, the dielectric cylinder for the injection of gas being located in the vicinity of said zones.

9. An ion source according to claim 8, wherein the cavity is excited in accordance with the TE_{122} mode.

10. An ion source according to claim 8, wherein the cavity is excited in accordance with the TE_{132} mode.

11. An ion source according to claim 1, wherein said microwave cavity is formed of a cylindrical cavity along the axis of which is disposed a hollow metallic cylinder having low reluctance which is in contact with the top wall of said cylindrical cavity and opens into said cavity in the proximity of said expansion cup aperture, said cylinder being part of the magnetic circuit which guides said static magnetic field.