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Design and Performance of a Hot Cathode Magnetically Collimated Arc Discharge Ion Source

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A hot cathode arc discharge type ion source is described. The discharge is collimated in an axial magnetic field and the ion beam is extracted axially. The maximum total ion current of the source, tested with hydrogen, is 42 ma. The extraction system allows focusing of almost 100% of this current. The limiting factor of the maximum ion current is analyzed. Although strong arc discharges could allow the extraction of higher ion currents, space charge spreading causes the ion beam to hit the front surface of the extracting electrode. Secondary electrons, released there, are focused back into the arc chamber producing instabilities of the source. A convenient means of regulation or modulation of the beam current is described. A magnetic analysis of the extracted beam shows about 34% atomic ion current.

INTRODUCTION

THE ion source described in this paper was designed to be used in a low-voltage and relatively high-current accelerator. It is the first ion source constructed in these laboratories in a program of development of a source for a very strong longitudinally extracted ion beam.

Although considerable work on ion sources based on the same working principle has been done[1–5] it seemed worth while to study the design of a convenient ion extracting system, which allows to focus practically the total ion current which leaves the source.

Furthermore it was of interest to get experimental information about the factors which limit the maximum obtainable useful beam current.

[1] R. Keller, Helv. Phys. Acta **22**, 78 (1949).
[2] Barnett, Stier, and Evans, Rev. Sci. Instr. **24**, 394 (1953).
[3] Bayley, Drukery, and Oppenheimer, Rev. Sci. Instr. **20**, 189 (1949).
[4] Bergstrahl, Dunning, Durand, Ellison, Howerton, and Slavin, Rev. Sci. Instr. **24**, 417 (1953).
[5] J. Kistemaker and H. L. Donwes Dekker, Physica **16**, 198 (1950).

DESIGN

Figure 1 shows a cross-section diagram of the complete equipment.

The arc chamber A of the source is drilled in a heavy copper cylinder which is introduced into the vacuum-tight brass jacket B. On the "cathode side" of the chamber, a diaphragm of 6-mm limits the radial arc extension. On the other side the arc chamber is limited by an "anticathode" C supported and insulated by means of the porcelain rings D. This electrode has a central perforation for ion extraction. Extraction apertures of 1.5, 3, and 6 mm have been tested.

The filament (1-mm diam tungsten) is mounted on a separate, easily removable unit which simultaneously

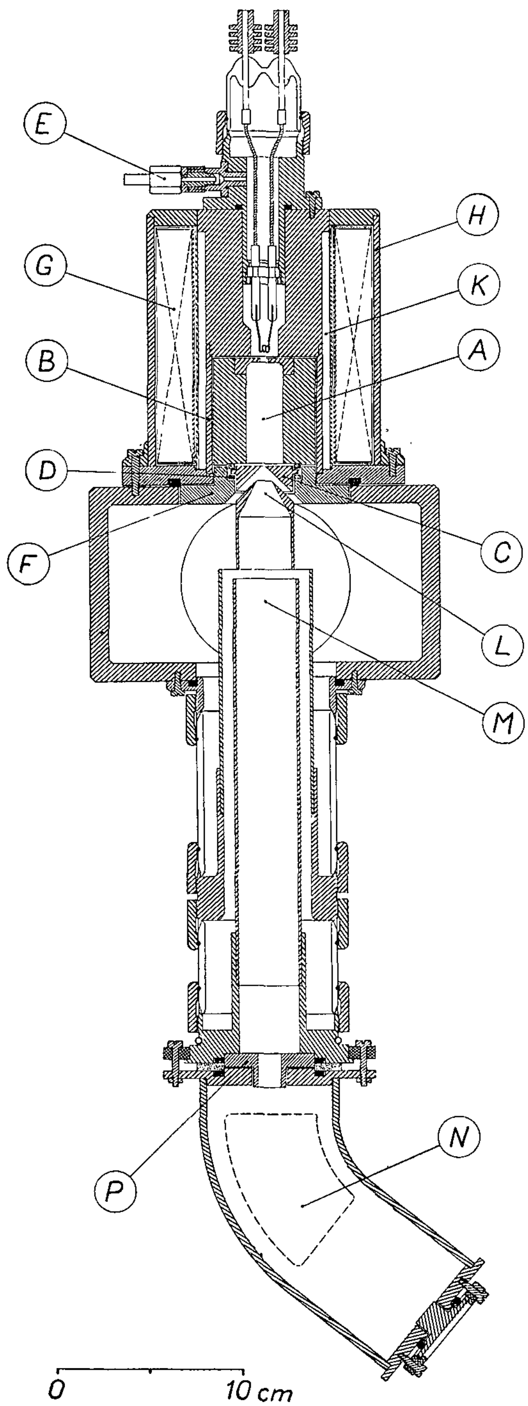

FIG. 1. Cross section of the equipment including the ion source, the extraction and focusing system, and the magnetic deflection chamber.

supports the connection E of the gas inlet. The filament unit projects inside an iron block which also acts as one of the pole pieces for the axial magnetic field. The opposite magnetic pole is formed by the anticathode and its supporting piece F. The magnetic coil G is mounted coaxially on the source body. The magnetic circuit is closed through the piece F and the external cylinder H. The body of the source and the magnetic coil are cooled by the water jacket K.

The source is mounted on a rectangular vacuum chamber located directly upon the baffle valve of a 4-in. oil diffusion pump. Through the opposite wall on this chamber are introduced the extracting and focusing electrodes L, M, respectively. Both electrodes are mounted coaxially and are supported by cylindrical glass insulators.

The front part of the extraction electrode is conically shaped. This form permits placing it closer to the ion outlet of the anticathode. The focusing is achieved by an electrostatic lens formed by the extractor and the focusing electrode.

The focusing of the beam has been calculated without taking into account space charge effects. According to the calculations the trajectories cross the axis of the system just in the plane of the extractor inlet. In this way no ions hit the front surface of this electrode and no secondary electrons are released there. Furthermore all calculated trajectories enter the focusing electrode.

Hence if no space charge effects are taken into account, it is to be expected that 100% of the beam extracted from the source can be focused on a target.

The beam, when not magnetically deflected, is introduced into an insulated cup (Fig. 2) placed at the other end of the focusing electrode. The distance between the inlet of the extractor electrode and the cup is 35 cm. In optimum focusing conditions, the beam diameter at the inlet of the cup is roughly 13 mm. A direct measurement of this value was performed by means of a fluorescent screen, and, with strong ion currents, by means of a thin copper foil perforated by the beam.

Figure 2 shows the schematic diagram of the circuit of the equipment. The source body is at ground potential, and the filament is biased negatively at the voltage of the arc power supply. The insulated anticathode of the source automatically works at about the same potential as the

TABLE I. Working parameters of the ion source for different anticathode apertures. Operation with hydrogen.

Anticathode aperture diameter	(mm)	*A* 1.5	*B* 3.0	*C* 6.0
Beam current (I)	(ma)	5	17	42
Total current (I_t)	(ma)	5	18	43.5
Extractor current (I_e)	(ma)	...	1	1.5
Extractor voltage	(kv)	5	13	17
Arc voltage	(v)	160	180	170
Arc current	(amp)	0.8	0.8	0.7
Source magnet	(g)	700	700	700
Arc chamber pressure	(μHg)	1.8	2	1.3
Vacuum tank pressure	(mm Hg)	10^{-5}	2×10^{-5}	3×10^{-5}
Hydrogen flow	(atmos cc/min)	0.1	0.4	1.2
Gas efficiency (taking into account the approximate content of H_1, H_2, and H_3 ions)		0.5	0.45	0.35

filament. The high-voltage power supplies of the extractor and the focusing electrode are connected in series.

RESULTS

The working parameters of the source depend on the size of the ion exit aperture in the anticathode. Table I shows typical values.[6]

In order to study the performance of the extraction system alone the focusing electrode power supply was eliminated and the focusing electrode was connected to the extractor through a 100-kΩ resistance.

In these conditions the focusing electrode acts as ion collector and the collector current in the resistance establishes a secondary electron repelling potential.

Under constant operation conditions of the source itself, the extractor voltage E_e was varied and the total current I_t, the extractor current I_e, and the collector current (beam current) I were registered.

Figure 3 shows a typical example of the values of I_t, I_e, I as functions of E_e. From the above-mentioned theoretical calculation of the extraction system it was to be expected $I_t=I$, the current I_e on the extractor being zero, and this situation should be independent of the extractor voltage E_e.

The curves show that for $E_e>13$ kv the beam current equals about 95% of the total current and the extractor current is almost zero. The currents do not depend on E_e.

For 9 kv$<E_e<$12 kv there is a strong interchange of currents between collector and extractor. Furthermore the I_t and I_e diagrams show a maximum for $E_e\approx 5$ kv.

This considerable increase of the total current for extractor voltage around 5 kv is supposed to be caused by a strong space charge spreading of the beam. For this reason, with low ion velocities, part of the beam hits the front surface of the extractor, and the total measured current is the sum of the ion current extracted from the source and secondary electron current released from the front surface of the extractor. For higher values of E_e with resulting higher velocities of the particles, the space charge effect is less important and it is possible to introduce the total ion current into the extractor. The beam is more collimated with a consequent sharp increase of the collector current.

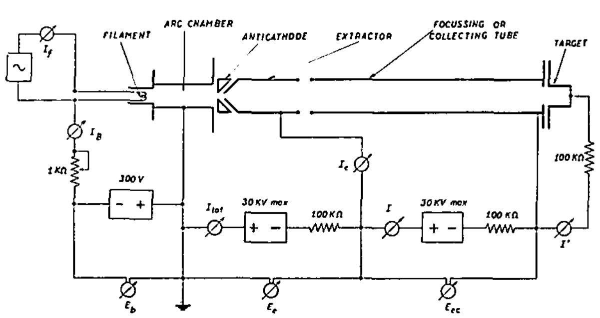

FIG. 2. Wiring diagrams.

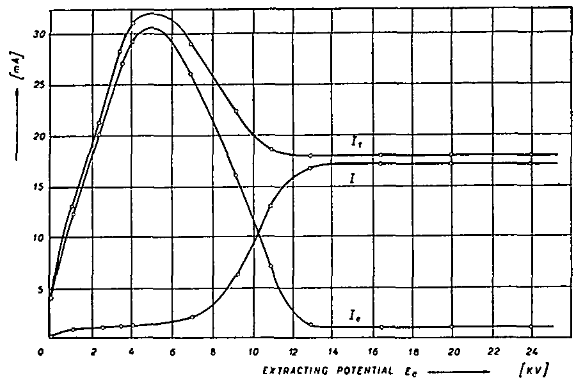

FIG. 3. Dependence of the collector (beam) current I, the extractor current I_e, and the total current I_t on the extracting voltage $-E_e$.

The supposition that space charge effects are responsible for the current dependences in Fig. 3 is consistent with the fact that for lower ion currents the "clean" situation, $I_t=I$, is reached at lower values of E_e (in Table I, column A, at $E_e=5$ kv).

The secondary electrons released from the extractor can produce serious trouble with stability of the source. In fact these electrons, crossing the extractor potential, acquire a considerable energy. Part of them enter the discharge chamber where they are trapped by the axial magnetic field and hit the cathode.

A local heating of the filament is produced with a subsequent increase of the arc discharge current, which could be compensated reducing the filament power (in some cases the source can be run without filament power supply).

At higher ion current and accelerating potentials a cumulative effect is produced; the source turns instable and the filament can be destroyed.[7]

So, in column C of Table I, where a beam current I of 42 ma is reached, it is difficult to avoid this instable situation produced at extractor potentials $E_e<17$ kv.

In any case, once the total beam enters the extractor, the source performance is absolutely stable.

At extracting voltage $E_e>18$ kv practically 100% of the total ion current leaving the source enters the focusing tube, acting as collector. As in Fig. 3, here the currents I_t and I almost coincide and do not depend on E_e. Once this stable situation is reached, there are no secondary electron currents returning from the ion collecting electrode.

With the 6-mm diameter aperture of the anticathode the arc current registered in Table I is 0.7 amp. Although it was relatively easy to establish considerably stronger arc discharges, it was impossible to reach a stable per-

[6] The "gas efficiency" is defined as the ratio of the real output ion current to the maximum possible ion current obtained if all the gas left the source in form of ions.

[7] W. A. S. Lamb and E. I. Lofgren, Rev. Sci. Instr. 27, 907 (1956), adopt a tungsten bar on the axis of the system just in the plane of the arc aperture, which captures the secondary electrons preventing their entrance in the arc chamber.

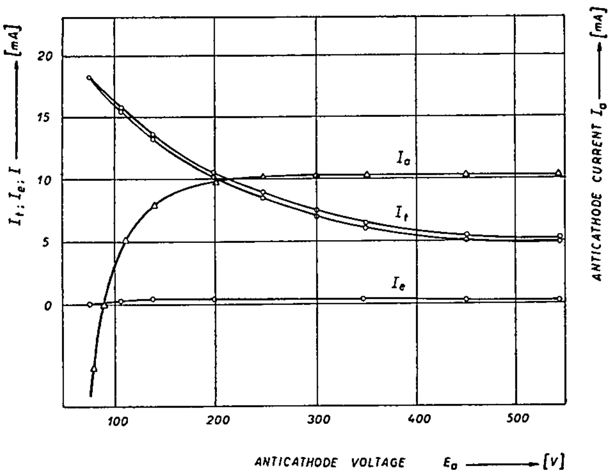

FIG. 4. Beam current I, extractor current I_e, and total current I_t as a function of the anticathode potential $-E_a$. The anticathode current I_a is also shown.

formance of the source at ion currents greater than about 40 ma.

It seems evident that the maximum obtainable beam current is not limited by the discharge mechanism of the source. This limitation is rather determined by the space charge spreading of the extracted beam and secondary electron return, leading to the described instabilities.

The foregoing results show, that in an attempt to construct a very strong ion source, emphasis should be placed on the design of an extracting system which avoids secondary electron return into the arc chamber for lower extracting voltages.

In a first experimental edition of the source, the anticathode potential could be controlled from outside. If a dc voltage $-E_a$ is applied to the anticathode, the beam current I results to be a decreasing function of E_a. In Fig. 4 the resulting dependence of the beam current I, the total current I_t and the extractor current I_e is shown. No influence of E_a on the focusing conditions; $I \approx I_t$, $I_e \approx 0$ of the beam is observed.

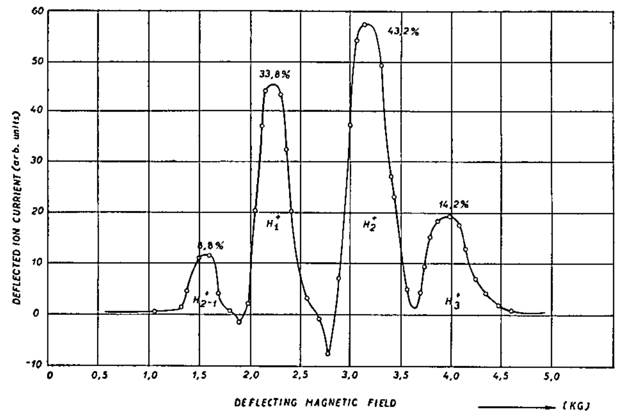

FIG. 5. Magnetic analysis of the hydrogen beam.

If the anticathode is not driven more positive than the cathode, there is no effect on the source discharge. In Fig. 4 the anticathode current I_a also is shown. I_a is zero for $E_a = 90$ v, i.e., 10 v more negative than the cathode. The value of 90 v is the floating voltage of the insulated cathode, measured with a high-impedance voltmeter.

The foregoing results suggest a simple method for control or modulation of the beam current without affecting the focusing of the beam and performance of the source, and without operating on the high-voltage power supplies.

The magnetic analysis was performed with the deflecting chamber N, Fig. 1, of rectangular cross section 20×65 mm. The beam enters the chamber through the iron diaphragm P. Figure 5 shows an example of the deflected beam current as a function of the applied magnetic field. About 34% of the total hydrogen current is atomic.

ACKNOWLEDGMENTS

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