ION SOURCES FOR CYCLOTRON APPLICATIONS

K. N. Leung, D. A. Bachman, D. S. McDonald, and A. T. Young
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720, USA

ABSTRACT

The use of a multicusp plasma generator as an ion source has many advantages. The development of both positive and negative ion beams based on the multicusp source geometry is presented. It is shown that these sources can be operated at steady state or cw mode. As a result they are very suitable for cyclotron operations.

1. INTRODUCTION

The Magnetic Fusion Energy (MFE) Group at the Lawrence Berkeley Laboratory (LBL) has been engaged in the development of neutral beam systems for fusion applications for the last twenty years. Large area positive hydrogen or deuterium ion sources designed at LBL have been selected and employed by various fusion research facilities in the US. In the next generation tokamak fusion reactors, high energy neutral beams will be needed for plasma heating and for current drive. In order to meet these future demands, negative hydrogen ion sources are also being developed by the MFE Group. These sources must generate amperes of H^-/D^- beams for steady-state operations.

The research on ion sources for fusion applications has led to the development of other types of ion sources, such as radio-frequency (RF) driven ion sources, high charge state ion sources, and multicusp sources capable of delivering almost pure H^+, N^+ or O^+ ions. Most of these ion sources can be operated in steady-state or cw mode. Therefore, they are also useful for most cyclotron applications.

2. HIGH CONCENTRATION H^+ ION SOURCES

Multicusp plasma generators have been used as ion sources for the production of positive and negative ion beams. These ion sources are capable of producing large volumes of uniform and quiescent plasma with densities exceeding 10^{12} ion/cm^3. For this reason, there was a great interest in the early 1980s in applying such devices as ion sources for neutral beam injection systems. To increase plasma penetration by a neutral beam, a high percentage of H^+ or D^+ ions is required. We had investigated the hydrogen ion species composition in a multicusp source with different magnet configurations. Experimental results indicated that the presence of primary ionizing electrons in the vicinity of the plasma electrode increased the percentage of the H_2^+ ions in the extracted beam.

To take advantage of this observation, a magnetic filter was incorporated into the multicusp ion source.[1] This filter, generated either by inserting small magnets into the source chamber or by installing a pair of dipole magnets on the external surface of the source chamber, provides a limited region of transverse B-field which is strong enough to deflect away high energy electrons but allow the plasma to diffuse into the extraction region. The absence of energetic electrons will prevent the formation of H_2^+ or D_2^+ in the extraction region and thus enhance the atomic ion species percentage in the extracted beam. It has been demonstrated that atomic species higher than 85% can be obtained routinely if a multicusp ion source is operated with a magnetic filter.

3. RF-DRIVEN POSITIVE ION SOURCES

A multicusp source can be operated with RF induction discharge to generate positive ion beams. There are several advantages of the RF driven plasma over the dc filament discharge plasma: (1) the RF discharge can be operated with all gases (including oxygen, which can easily poison tungsten filament cathodes); (2) power for heating the cathode is avoided; (3) there are no short life components in the source; (4) a clean plasma free from contamination from the cathode material can be maintained; and (5) the RF power supplies operate conveniently at ground potential.

At LBL, an RF driven multicusp source has been operated in both cw and pulsed modes to generate various positive ion beams. A schematic diagram of a 10-cm-diam RF ion source is shown in Fig. 1. The

RF antenna is fabricated from 4.7-mm-diam copper tubing and is coated with a thin layer of hard porcelain material. The thin coating is slightly flexible and resistant to cracking. It has maintained a clean plasma in cw operation for periods of a week or more; the antenna life expectancy has not yet been determined.

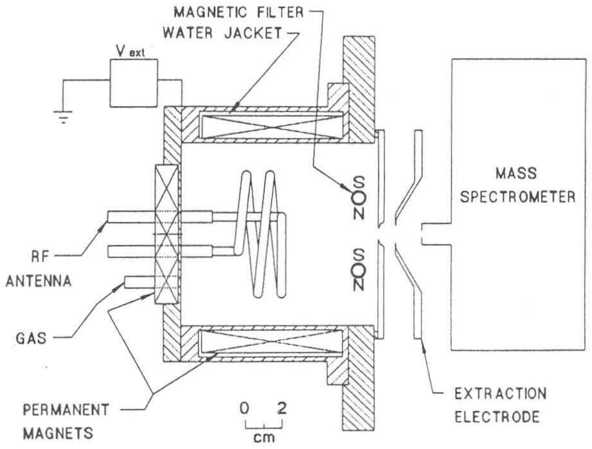

Fig. 1 Schematic diagram of the RF multicusp ion source.

The RF multicusp source has been tested with inert gas plasmas such as He, Ne, Ar, Kr and Xe. Figure 2 shows the extractable positive ion current (and current density) as a function of RF power when the filter rods are removed. The optimum source pressure is typically below 1 mTorr. It can be seen that the output currents increase almost linearly with RF input power. In most cases, the extractable ion current density can be as high as 1 A/cm^2.

We have investigated the hydrogen ion species composition in the RF driven source with and without the magnetic filter. Figure 3 shows the hydrogen ion species distribution as a function of RF power when the filter is in place. The H^+ ion concentration increases from 80 to 97% as the RF power is varied from 12 to 30 kW. The highest current density achieved is about 1.5 A/cm^2.

We have operated the RF driven source with a nitrogen plasma. Similar to the hydrogen discharge, the atomic ion concentration increases with the RF input power. A nearly pure (>98%) N^+ ion beam with current densities in excess of 500 mA/cm^2 has been obtained when the magnetic filter is employed.

In addition to hydrogen and nitrogen, we have also operated this ion source with other diatomic gases such as oxygen. Oxygen plasmas are usually produced by either RF or microwave discharges. It is difficult to use a dc discharge with tungsten filaments because electron emission deteriorates very fast when oxygen is present. The porcelain-coated antenna has been operated very successfully with an oxygen plasma both in pulsed and cw modes. Atomic ion concentration higher than 93% can be achieved with approximately 16 kW of RF power. The extractable ion current density is found to be greater than 500 mA/cm^2.

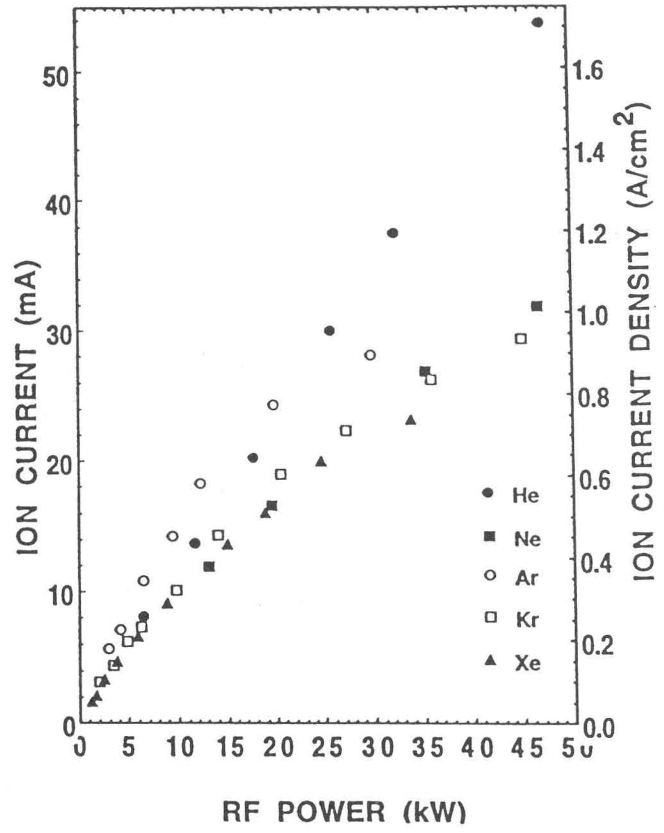

Fig. 2 Extracted beam current and density as a function of RF power for various inert gas plasmas.

4. NEGATIVE ION SOURCES

H^- ions are used extensively in particle accelerators such as cyclotrons, tandem accelerators and proton storage rings. In order to heat plasmas and to drive currents in future tokamak fusion reactors, multiamperes of very high energy neutral beams will be required. The high neutralization efficiency of H^- or D^- ions enables them to form atomic beams with energies in excess of 200 keV. At LBL, two different types of H^- ion sources have been investigated and developed by the MFE Group.

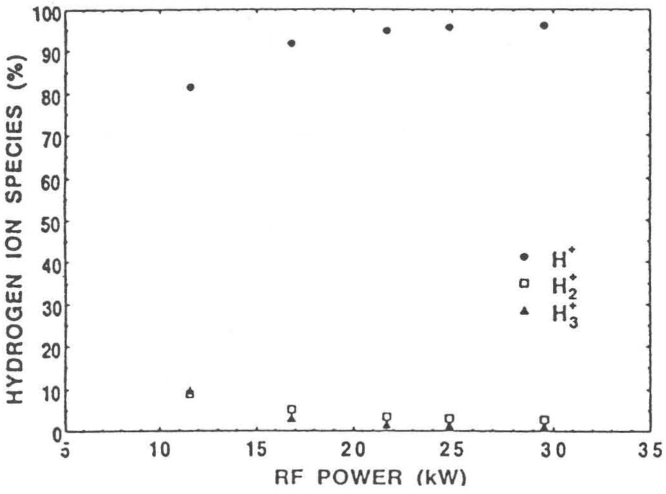

Fig. 3 Hydrogen ion species as a function of RF power when the source is operated with the filter.

4.1 Surface Conversion Negative Sources

Figure 4 shows a LBL type surface conversion source. In this ion source, a water-cooled molybdenum converter is inserted into the multicusp plasma generator. By biasing the converter negatively with respect to the plasma, positive ions are accelerated across the sheath and impinge on the converter surface. H^- (or other negative ions) that are formed at the converter are then accelerated back through the sheath by the same potential. The bias voltage on the converter thus becomes the negative ion extraction potential. The converter surface is normally curved to geometrically focus the negative ions through the plasma to the exit aperture.

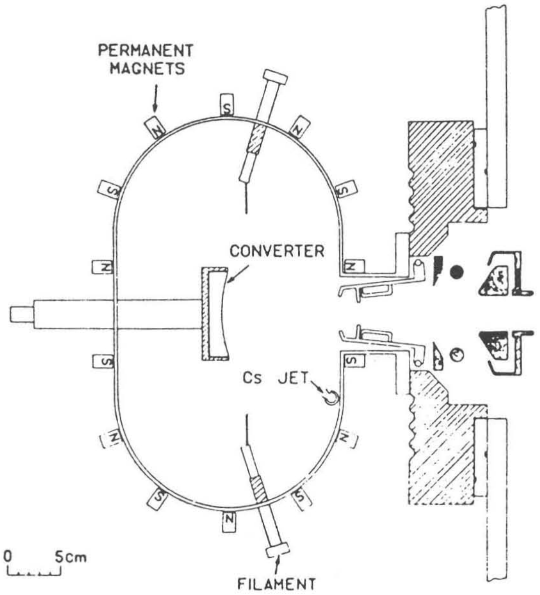

Fig. 4 A schematic diagram of the multicusp surface conversion negative ion source.

The advantages of the surface conversion source are low source operating pressure and very small electron content in the self-extracted negative ion beam. The source can be operated either in steady-state or pulsed mode. However, source operation always requires the presence of cesium which can cause voltage breakdown in the accelerator column. Nevertheless, steady-state H^- beams with currents greater than 1 A have been generated by this type of surface conversion source.[2] Production of other negative ions (such as Au^-) by this type of source have been reported by Mori and Alton.[3]

4.2 Volume Production Negative Ion Sources

A hydrogen plasma contains not only positive ions and electrons, but also H^- ions. In 1983, a novel method of extracting volume-produced H^- directly from a multicusp source was reported by Leung et al.[4] In this H^- source, a magnetic filter divides the source chamber into a discharge and an extraction region. Excitation and ionization of the gas molecules are performed by primary electrons in the discharge region. In the extraction region, the low electron temperature makes it favorable for the production and survival of H^- ions.

It was demonstrated in 1984 that the filter-equipped multicusp source could provide high quality H^- beams with current densities ~38 mA/cm^2.[5] In 1988, a small 7.5-cm-diam multicusp source has been operated successfully to generate H^- ions in a pulsed mode. From this compact volume source, an H^- current density greater than 250 mA/cm^2 has been extracted.[6] In order to improve the lifetime of the volume source, RF induction discharge has been employed in a manner described in section 3. To date, an H^- current of ~40 mA can be obtained from a 5.6-mm-diam aperture with the source operated at a pressure of about 12 mTorr and 50 kW of RF power.[7]

The multicusp source has also been employed to generate volume-produced C^- ions for Cyclotron Mass Spectrometry (CMS) applications. In this case, the C^- ions are extracted directly from a CO or CO_2 discharge plasma. Thus, the tedious graphitization process in a surface conversion source is avoided. Figure 5 shows the mass spectrum of the accelerated beam when CO_2 is used in the discharge. Work is now in progress to incorporate this new volume-production C^- source into the compact permanent magnet cyclotron spectrometer.

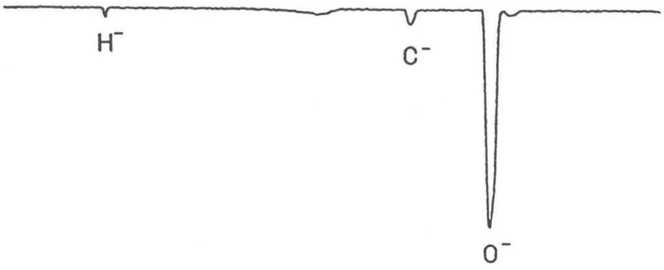

Fig. 5 Negative ion species from a CO_2 gas filament discharge.

5. HIGH CHARGE STATE MULTICUSP SOURCE

Multicusp generators can confine primary electrons very efficiently. Since the magnetic fields are localized near the chamber wall, large volumes of uniform and high density plasmas can be obtained at low pressure, conditions which favor the formation of high charge state ions. Attempts have been made at LBL to generate multiply charged ion beams by employing a modified multicusp source. Experimental results demonstrate that charge state as high as +7 can be obtained with argon or xenon plasmas.[8] Total ion current densities higher than 63 mA/cm^2 have been achieved with a discharge voltage of 400 V and a discharge current of 100 A. However, additional work is needed in order to extend the charge state to values higher than +7. If this is successful, the multicusp source will become very useful for accelerator and high energy ion implantation applications.

6. METALLIC ION BEAM GENERATION

We have operated a multicusp source to generate positive copper ion beams by using a background DC filament argon discharge. The plasma electrode was made of copper and biased at approximately 200 volts negative with respect to the anode allowing the neutral copper atoms to be sputtered from the plasma electrode. These copper atoms are subsequently ionized in the plasma and become positive copper ions. These positive copper ions will fall back towards the extraction aperture and be accelerated. Figure 6 shows an extracted beam spectrum which contains the background argon ions as well as the copper ions. With a total filament discharge power of 80 volts at 5 amperes, 120 microamperes of positive ion current was extracted. The beam was composed of 57% argon ions and 43% copper ions, giving a total copper beam current of 51 microamperes. Extracted through a 1.0mm diameter hole, the copper ion current density was 10 mA/cm^2.

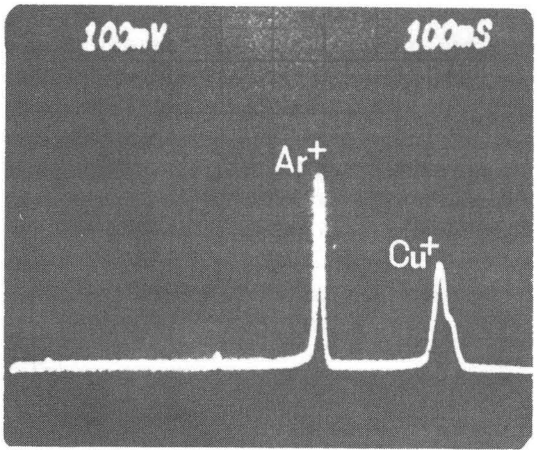

Fig. 6 Spectrum of Cu^+ from a small multicusp source.

ACKNOWLEDGMENT

This work is supported by the U.S. Dept. of Energy, Division of Advanced Energy Projects, Office of Basic Energy Sciences under Contract No. DE-AC03-76SF00098.

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