VERY-LOW-ENERGY-SPREAD ION SOURCES*

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Abstract

Axial ion energy spread of multicusp sources has been measured by three different techniques: an electrostatic energy analyzer for plasma ion measurement at the source exit; a magnetic deflection spectrometer; and a retarding-field energy analyzer for measurement of the accelerated beam. By introducing a magnetic filter inside the multicusp source chamber, it is shown that the energy spread of positive hydrogen ions can be reduced to approximately 1eV. The energy-spread values for H^- ions are lower. New ion source configurations are now being investigated to further reduce the ion energy spread to below 1 eV and maximize source performance reliability and lifetime.

1 INTRODUCTION

The multicusp source has been the ion source of choice for many applications due to its capability to produce large volumes of uniform, quiescent and high-density plasmas with high electrical and gas efficiencies. Recently, new applications have found use for multicusp ion sources because of their capability to generate ion beams with low axial energy spread. Some of these applications are ion projection lithography where low axial or longitudinal energy spread (< 3eV) is required to minimize the chromatic aberrations of the projected pattern [1]. In radioactive ion beam projects for nuclear physics experiments, an ion source with axial energy spread of less than 1 eV is needed to perform isobaric separation with a magnetic deflection spectrometer [2]. In low energy ion beam deposition processes, very low energy spread is required in order to separate and focus the ions properly [3]. In neutron time-of-flight experiments, a low energy-spread beam is needed to obtain a well defined short pulse [4].

This article reviews different techniques for measuring the axial ion energy spread of the multicusp ion source. It is demonstrated that the presence of a permanent-magnet filter can reduce the ion energy spread from 6 eV to approximately 1 eV for moderate discharge power. The energy spread of the H^- ions is generally lower than the source reliability and lifetime, various ion source configurations (such as the RF-driven and the co-axial type multicusp source) are being investigated. Preliminary results are presented in this article.

2 EXPERIMENTAL ASSEMBLY

6.1 Ion Source Arrangement

The ion source tested have a multicusp generator arrangement: the external surface of the source chamber is surrounded by columns of samarium-cobalt permanent magnets with alternating polarity. These magnets generate longitudinal line-cusp magnetic fields that can confine the primary ionizing electrons efficiently. One end of the chamber is terminated by an end flange which is covered with rows of permanent magnets. The open end of the chamber is where the energy analysis takes place. As shown in Fig. 1, a magnetic filter system can be installed in the source chamber which provides a limited region of transverse magnetic field and divides the chamber into two regions: (1) the discharge or source chamber, where the plasma is formed and contains the energetic ionizing electrons and (2) the extraction chamber, where a plasma with colder electrons is found.

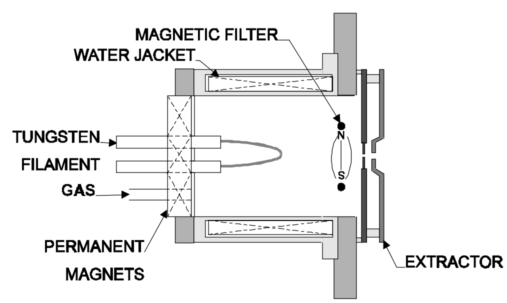

Figure. 1 Schematic of a multicusp ion source when is operated with a filament cathode.

Two different types of multicusp source configurations have been tested: dc filament-discharge ion source, rf-

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driven source. In the filament discharge, a steady-state plasma is produced by primary electrons emitted from a tungsten filament. The source is normally operated with a discharge voltage of 70 V and a discharge current between 2 - 10 A. In the rf-driven source, the tungsten filament of the filament discharge source is replaced by an rf-antenna operating at a frequency of 13.56 MHz. The antenna is fabricated with copper tubing and is coated with a thin layer of porcelain which enhances the discharge efficiency and prolongs the source lifetime.

2.2 Axial Energy Spread Measurement Methods.

A gridded retarding field energy analyzer has been used to study the longitudinal energy spread of the positive ion species at the plasma or first electrode [5]. The ion source and the energy analyzer assembly is illustrated in Fig.2. The energy analyzer contains a fine-meshed grid which is biased negatively for electron suppression and a collector for energy distribution measurement. The energy analyzer is connected to a computerized data acquisition system, cosisting of a computer and two multimeters.

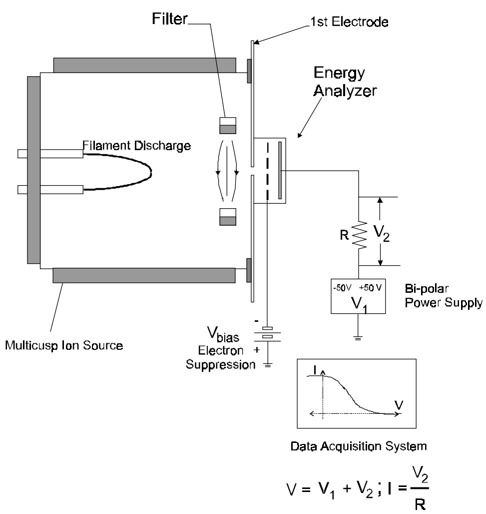


Figure. 2 Schematic of the ion source with the removable filter and the retarding field energy analyzer at the source aperture assembly.

This technique does not require an acceleration system and it measures the true ion energy spread of the source. In this arrangement, the collected ion current as a function of bias voltage is first measured. The I-V characteristic is then differentiated to determine the energy spread (ΔE) which is defined as the full width at half maximum (FWHM) of the differentiated curve.

A three-electrode extractionn system with a 0.6 mm diameter aperture has been used for beam formation. In normal operation, the ion source and the first electrode are electrically biased at 7 kV, and the second electrode at -1 kV with respect to the ground potential. The last or third electrode is connected to ground. In this configuration, the second electrode operates as a suppresser to prevent backstreaming electrons from accelerating back to the ion source.

The retarding-field energy analyzer is used to measure the axial energy spread of the accelerated beam. Fig. 3 shows the experimental setup which includes the ion source, the extraction system and the retarding field energy analyzer. The expanding beam is collimated well enough that the ion trajectories are almost parallel by the time they reach the collector plate of the enrgy analyzer. The collector plate, where the energy analysis takes place, is electrically connected to the ion source. A small battery or variable power supply is used to adjust the collector plate potential to $\pm$ 90 V with respect to the source. The acfcelerated beam is slowed down by the time it reaches the collector plate in order to avoid high energy beam heating on metal.

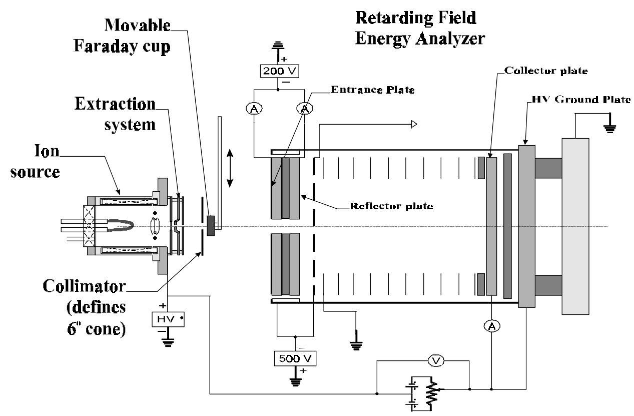


Figure. 3 Schematic of the retarding field energy analyzer system for accelerated beam energy spread measurements.

The magnetic energy analyzer is used to measure energy spread of various positive ion species and H^- ions in the accelerated beam. A schematic of the source with the magnetic energy analyzer is shown in Fig. 4. The enrgy spread can be inferred from the output spectrum of the ion species. Each peak in the distribution has a finite width due to the axial energy spread of individual species [6].

The magnetic field B applied to deflect a singly charged ion of mass M and energy E to a gyroradius R is given by

$$B(\text{Gauss}) = 144\ [\mu E(\text{eV})]^{1/2} / R(\text{cm})$$

where $\mu = M/M_p$ and M_p is the proton mass. As shown in the schematic of Fig. 5, the energy of the individual ion peaks is the same and the distance along the x-axis (the B-field) is proportional to $(ME)^{1/2}$. The center of the individual ion peak is the average energy of the extracted ion beam species. ΔE is the difference between E_2 and E_1. The energy spread also includes the instrumental contribution to the width which provides the upper limit of the energy spread.

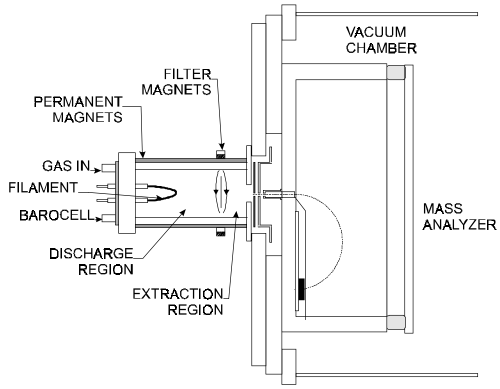


Figure. 4 Schematic drawing of a filament operated multicusp ion source mounted in a vacuum chamber. A magnetic analyzer is used for analyzing the collimated and accelerated beam.

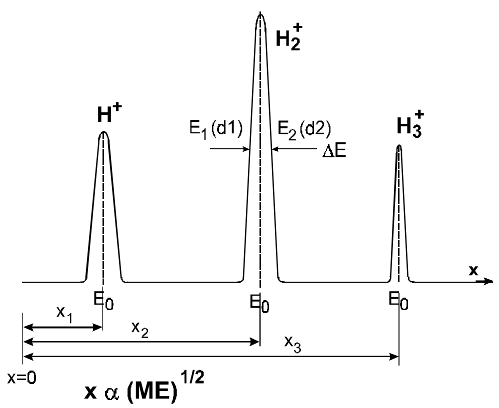
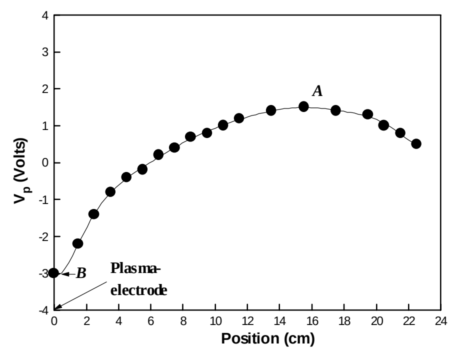


Figure. 5 The axial energy spread is found from the ion species traces. The energy of the individual ion peaks is the same and the distances are proportional to $(ME)^{1/2}$. The position of the individual ion peak center is the average energy of the extracted ion beam species.

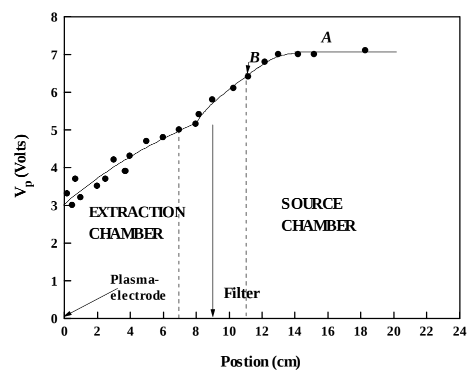
3 EXPERIMENTAL RESULTS

The results for the different analyzing methods are consistent. As expected, the axial energy spread of the ions is lower with the presence of filters than without [5]. When the source operates without a filter, the axial plasma potential decreases monotonically towards the plasma electrode, as shown in Fig. 6a. ***A*** and ***B*** are the maximum and minimum plasma potential values where ions can be formed. Ions formed at position ***A*** have more energy than ions formed in position ***B***, given by the difference in potential between the two points. Positive ions generated at high plasma potential (V_p) will reach the extractor as well as the ions created at lower potentials. Since the ions are generated at positions with different plasma potential, they will have a spread in axial energy when they arrive at the extraction aperture. Due to the presence of primary electrons everywhere in the source, ionization may take place in the plasma sheath of the extraction aperture [5].

The presence of the filter reduce the energy spread since it create a region with a relatively uniform V_p profile in the discharge chamber region, as shown in Fig. 6b. Primary electrons are confined in the source chamber by the filter magnet fields as well as the multicusp field on the chamber walls. The potential gradient in the extraction region produces no effect on the energy spread. Since positive ions are produced within the source chamber region, they arrive at the plasma electrode with about the same energy due to the uniform V_p distribution. However, there is still a small potential gradient, given by the potential difference between point ***A*** and ***B*** (approximately 1 V), between the center and the filter region that causes a small spread.



a)

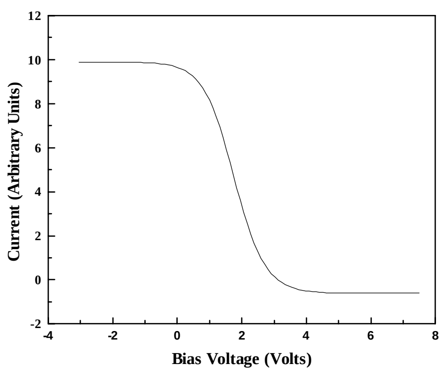


b)

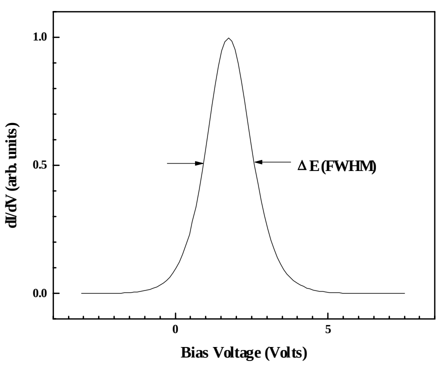
Figure. 6 (a) Axial plasma potential profile inside the source in the absence of a magnetic filter. (b) Axial plasma potential profile inside the source in the presence of a filter.

3.1 Energy spread analysis at the source exit

The axial energy spread at the source exit of filament driven ion sources without the magnetic filter ranges from 3 to 7 eV under different conditions of discharge current, and pressure. A typical I-V characteristic curve and its corresponding differentiated curve are shown in Fig. 7a and 7b. The data in Fig. 8 show that ΔE decreases with increasing pressure when the plasma electrode is connected to the anode. At high source operating pressures, ionization takes place close to the filament cathode. Primary electrons do not reach the extraction region where V_p is decreasing rapidly. Secondary emission electrons originating from the plasma electrode will not have enough energy to ionize the neutral particles (similar to the effect of a filter) [5]. The energy spread of the source without filter increases with the increase of discharge current due to the increase of the plasma potential, as shown in Fig. 9. Such effects are absent in the case with filter because the relatively uniform plasma potential distribution remains in the discharge chamber.



a)



b)

Figure. 7 (a) The I-V characteristics of the energy analyzer for the filament discharge source. (b) The I-V curve of Fig. 5a is differentiated to obtain the axial energy spread.

3.2 Retarding field enerergy analyzer measurements for accelerated beams.

After accelerating the beam to 7 keV, the axial energy spread of the filament-driven source without filter is on the order of 5 eV due to the larger plasma potential variation inside the source where ions are formed. In the presence of the magnetic filter, ΔE is found to be 3.3 eV at a discharge current of 9 A. At a discharge current of 1 A, the axial energy spread is 1.2 eV.

The axial energy spread of the accelerated beam of the rf-driven multicusp ion source was measured with the rf power supply operated at ground potential. Voltage isolation is obtained by using a transformer with sufficient insulation in the matching circuit. Initial measurements of the axial ion energy spread for accelerated beam from the rf source were greater than 100 eV, very large compared to the measured values of 2 to 3 eV for filament discharge cases. This measured energy spread is comparable to the value that have been reported by Zackhary [7] and Olthoff et al [8].

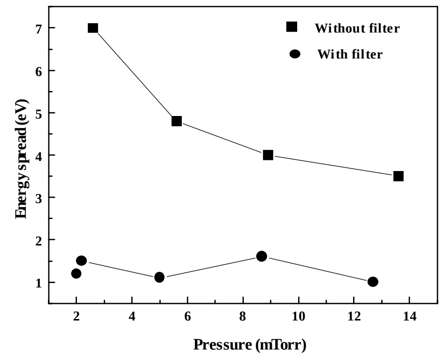


Figure. 8 Pressure vs. energy spread for a 10 cm diameter source with and without a magnetic filter.

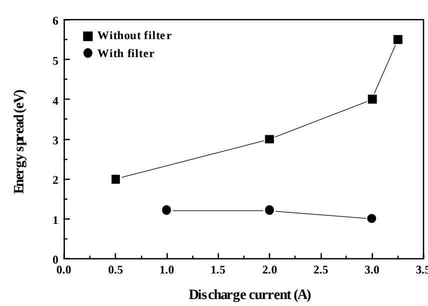


Figure. 9 Discharge current vs. energy spread for a 10 cm diameter source with and without a filter.

The large axial energy spread of the rf source may have been due to the rf voltage coupling to the extraction voltage, thus resulting in a modulation of the beam energy. The rf modulation has been eliminated through the following steps. Problems associated with ground loops between the measurement devices and the data acquisition circuits have been minimized with the use of fiber optics for electrical isolation and with longitudinal chokes (neutralizing transformers). Longitudinal chokes are used to eliminate longitudinal currents within the ground loop, while having an insignificant effect on the signal current [9].

The axial energy spread is reduced when the rf power supply is installed at the high voltage platform, so that it is operated at the same potential as the ion source. The leads between the matching network and the induction coil are shielded to reduce the energy spread. Operating the rf power supply at the extraction potential enables complete shielding of the leads between the matching network and the induction coil. A voltage isolator between the matching network and the source is no longer required. Furthermore a set of capacitors that function as a low-pass filter can eliminate the modulation of the dc acceleration voltage with rf-interference. With all these modifications, the axial energy spread was reduced to 3.6 eV at 1 kW, which is approximately the same value as the filament discharge case.

3.3 Magnetic energy analyzer.

The ion species distribution for energy spread analyses is obtained by the use of the magnetic deflection mass spectrometer. In the distribution, each peak has a finite width due to the axial energy spread of individual species. The axial energy spread is defined in this case as the full width at half maximum (FWHM) of the peak signals. The advantage of using this method is that the energy spread of each species of hydrogen can be evaluated. The energy spread of H^+ ions has been found to be 2.3 eV, H_2^+ 2 eV and H_3^+ 1.7 eV.

This technique can be used to measure the axial energy spread for H^- ion as well. It has been found to be 1 eV, half of that of the positive ions. H^- ions are formed in the extraction region. Since the plasma potential gradient in this region is small, the H^- ion energy spread is expected to be lower than that of the positive ions [10].

4 ADVANCED ION SOURCE CONCEPTS

Ion source operation with a tungsten filament results in an erosion of the material that could contaminate the source and limit the lifetime. The RF-driven discharge is cleaner, and it does not have the lifetime limitation seen in the filament discharge. In the RF-driven source, an induction coil or antenna is used for the discharge. The antenna can be made of different materials: copper, aluminum, porcelain or glass coated copper, etc.. The porcelain coated antenna can better withstand the ion bombardment from the plasma and electrical as well as thermal damages than other known types of antennas. Furthermore, the coated antenna is more energy efficient since it eliminates the short-circuit between the plasma and the bare coil. With the increasing RF power requirements and different plasma conditions, the porcelain coated antenna sometimes fails to perform satisfactorily. A new antenna using quartz has been designed that will provide a longer lifetime and cleaner operation of the source.

In general, it has been demonstrated that the filament-discharge, rf-driven sources have relatively low axial energy spread on the order of 1.7 to 3.6 eV with the use of the magnetic filter that levels the plasma potential distribution in the discharge region. These axial energy spread values are acceptable for some applications but even smaller values are needed for other experiments. A new ion source design (co-axial source) that could deliver an energy spread of less than 1 eV is being constructed and tested at LBNL. Results of its development will be reported in a near future.

5 ACKNOWLEDGEMENT

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