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ABSTRACT

To study the effects of frequency on an electron cyclotron resonance (ECR) ion source, the LBL Advanced ECR ion source (designed to operate at 14 GHz) has been tested at 6.4, 10, and 14 GHz with one plasma chamber (ID = 6.0 cm), a permanent sextupole magnet ("closed sextupole") with a field strength of 0.84 Tesla at the chamber wall, and no radial vacuum pumping. Pure oxygen was used as the running gas for a fair comparison. The source was tested as a single stage, as well as with cold electron injection using an electron gun in place of a conventional microwave-driven first stage. Higher frequency, with a higher axial magnetic field to ensure a closed ECR zone for electron heating, does give better performance. As demonstrated before, at each frequency electron injection led to about a factor of two increase in the high charge state oxygen beam intensity. The 14 GHz performance of the AECR source with the closed sextupole magnet was compared to the "slotted sextupole" (a plasma chamber with radial pumping slots of 7.0-cm dia and a weaker magnet of 0.64 Tesla at the chamber wall). Results show that a stronger sextupole magnet alone does not automatically improve the source performance.

1. INTRODUCTION

Development of Electron Cyclotron Resonance sources for production of high intensity and high charge state ion beams began in the early '70s.[1] The detailed operation of ECR sources involves control of many parameters including frequency,[2] magnetic field profile and strength, gas mixing,[3] plasma confinement, and microwave heating. How these parameters affect performance is still being studied. Frequency scaling in ECR sources was first predicted and then demonstrated on various ECR sources by Geller, et al.[2] Scaling predicts that the plasma density in ECR sources should increase as the square of frequency just as the plasma critical density does. Thus, by running at a higher frequency the ECR source should produce higher charge state ion beams with higher intensities. In the past few years ECR development has been centered on higher frequency and higher magnetic fields.[4] ECR sources around the world operate at frequencies between 2.5 and 18 GHz. Sources at 35 GHz and higher have been proposed.[5,6] In general, sources operating at higher frequencies with higher axial and radial magnetic fields work better. However, the CAPRICE ECR[7] ion source, which operates at 10 GHz, has produced results comparable to 14 GHz sources. CAPRICE has a microwave coaxial feed mechanism and very strong mirror and sextupole magnetic fields. It has also shown very good long-term stability. Therefore the question of whether the frequency or magnetic field, either axial or radial, enhances ECR performance the most, is still open.

The ECR Group from Michigan State University reported the NSCL (National Superconducting Cyclotron Laboratory) superconducting ECR ion source running at 6.4 GHz, with a sextupole magnetic field strong enough for running at 14 GHz, can produce good stability at about the same beam intensity as it has at 14 GHz.[8] Can higher sextupole magnetic fields alone improve the source performance on every ECR ion source? If so, new ion sources could be built with strong sextupole fields and operated at lower frequencies and reduced costs. Clarifying the effect of the sextupole magnetic field on the ECR source performance would give better understanding of the physics process involved in ECR ion sources.

2. DESCRIPTION OF THE AECR

Tests at 6.4, 10, and 14 GHz were carried out on the LBL Advanced ECR (AECR) ion source, which is designed to operate at 14 GHz. Figure 1 illustrates the design of the AECR. A detailed description of this source can be found elsewhere.[9,10] Microwaves are launched on axis by making a transition, from a rectangular waveguide to a circular waveguide, inside the injection region. An iron plug added to the injection region increases peak axial field to more than 1 Tesla. The sextupole field is produced by a Nd-Fe-B multipole magnet. Pumping for the copper plasma chamber and the extraction region is provided by a 240 and a 500 l/s turbomolecular pumps, respectively. A lanthanum hexaboride (LaB_6) electron gun is installed at the location of a conventional microwave-driven first stage as indicated in Fig. 1. It injects cold electrons axially into the plasma chamber.[10]

The sextupole magnet was originally designed as a slotted sextupole, to accommodate radial vacuum pumping, oven access, and solid material insertion. This limited the field strength to 0.64 Tesla at the plasma chamber wall as shown in Fig. 2. The internal diameter and the length of the plasma chamber are 7.0 cm and 30 cm, respectively. During the initial tests, using the electron gun, the AECR ion source has produced intense, high charge state ion beams.[10] For example, 131 eμA of O^{7+} and 475 eμA of O^{6+} were produced. Typically, the gun was biased at 50 to 150 V and produced bias currents of 20 to 100 mA. The source showed very good short-term stability, but its long-term stability was not sufficient for regular operation with the 88-Inch Cyclotron at Lawrence Berkeley Laboratory. Based on the reports mentioned in the introduction, we suspected that the reduced long-term stability was caused by a weak sextupole field. Thus, a modified plasma chamber was built. It eliminated the pumping slots and reduced the chamber ID from 7.0 to 6.0 cm. This "closed sextupole" design has increased the sextupole field at the plasma chamber wall from 0.64 to 0.84 Tesla, a 30 percent increase over the field strength shown in Fig. 2.

3. PERFORMANCE AT VARIOUS FREQUENCIES

Performance of the AECR at 6.4, 10, and 14 GHz with pure oxygen gas for the two mode operations is presented below. First, with the electron gun injecting cold electrons axially into the plasma chamber; second, the source was run as a single stage source.

Results with the closed sextupole are shown in Fig. 3 for the cold electron injection and Fig. 4 for the single stage mode operation. The source was tuned to optimize the O^{6+} and O^{7+} ion beam currents. During the tests, the axial magnetic field was scaled in proportion to each frequency to ensure a closed ECR surface for electron heating. At 14 GHz and with cold electron injection, no improvement in output was observed for the closed sextupole compared to the slotted sextupole. Comparison to the initial tests[10] with the slotted sextupole shows the output intensities for O^{7+} and O^{6+} actually were down by factors of 5 and 3, respectively.

At lower frequencies, the source produced lower outputs as can be clearly seen in Fig. 3 and Fig. 4. At 6.4 GHz and single stage mode operation, the source produced virtually no x-rays and the output intensities for O^{6+} and O^{7+} were down by factors of 20 and 100, respectively, compared to the 6.4 GHz LBL ECR.[11] The explanation for reduced output may be that the microwave power was not efficiently coupled to the plasma thus the electron density and temperature were low. At 6.4 GHz, tests were also done to raise the axial field to construct a very high mirror field configuration (like the CAPRICE source at 10 GHz), but no enhanced beam output was observed. Plasma died out as soon as the fundamental ECR zone was eliminated. At 10 GHz, the output for O^{6+} and O^{7+} increased, as shown in Fig. 4, by factors of 5 and 10 respectively. The x-ray level also increased. Such outputs are still lower than other 10 GHz ECR sources.[7] At each frequency with cold electron injection, compared to the single stage mode operation, the high charge state oxygen ions increased a factor of two or higher as demonstrated previously at 14 GHz.[10]

Tests at these three frequencies have shown the source tuning parameters were still very critical to the source output. A change less than half percent of the microwave power, axial magnetic field, or neutral gas input can cause the source become unstable. One could at times tune the source into a very quiet mode with above indicated output for a period of a few hours. Then, the source would jump spontaneously to an unstable mode with very low output and a higher x-ray level. In a comparison between the original sextupole and the stronger sextupole at 14 GHz, the source long-term stability is just slightly improved and still not sufficiently stable for regular operation with the cyclotron.

4. DISCUSSIONS AND CONCLUSIONS

The motivation for building a stronger sextupole magnet is to maintain or enhance the source output and improve its long-term stability. As these tests have shown, the AECR ion source operating at 6.4, 10, and 14 GHz with the stronger sextupole magnet, only minor improvement of long-term source stability has been observed. In this study, the output of O^{7+} ions is better when the source is operating at higher frequency. Maximum beam output of O^{7+} with the stronger sextupole actually dropped a factor of 5 compared to the AECR performance with the slotted sextupole. Such reduced output indicates that the source is running at low plasma density. The low density plasma is thought to be due to poor microwave coupling, since the plasma chamber size has been changed (the cavity r-f operating mode could have changed). When the ion source is running at low plasma density with no radial vacuum pumping, neutral gas pumping is not sufficient.

The criticality of the source tuning parameters may be caused by the high Q of the plasma chamber. It is made from copper and the resonances allowed in the cavity may not overlap each other. Jumping between r-f modes is likely to happen as plasma is produced. The estimated power absorbed in the plasma is about 20 percent of the input microwave power.[12] This won't load down the cavity enough to lower the Q. A lower Q test was carried out by inserting a stainless steel liner into the copper chamber to reduce the chamber Q by a factor of ~7. At 14 GHz the source produces about the same output as the copper chamber, but the long-term stability is dramatically improved, as is the source tunability. The output intensity is linear with the axial magnetic field over a few percent of field change and, to a great extent, to the input microwave power. This could indicate that the ECR source should not be operated with a very high Q chamber unless all the allowed cavity modes overlap each other. The best Q value for an ECR ion source at a specific configuration should be given further and more detailed study in future.

We have concluded from this study that a high sextupole magnetic field along does not automatically improve the source performance. Source performance can benefit from a strong sextupole field if the microwave power can be efficiently coupled to the plasma, as does the CAPRICE source. For the same strong sextupole field, a higher frequency and a higher axial magnetic field, the ECR source can produce more beam output. This is consistent with frequency scaling. AECR source long-term stability may ultimately depend upon the optimum Q value of the plasma chamber.

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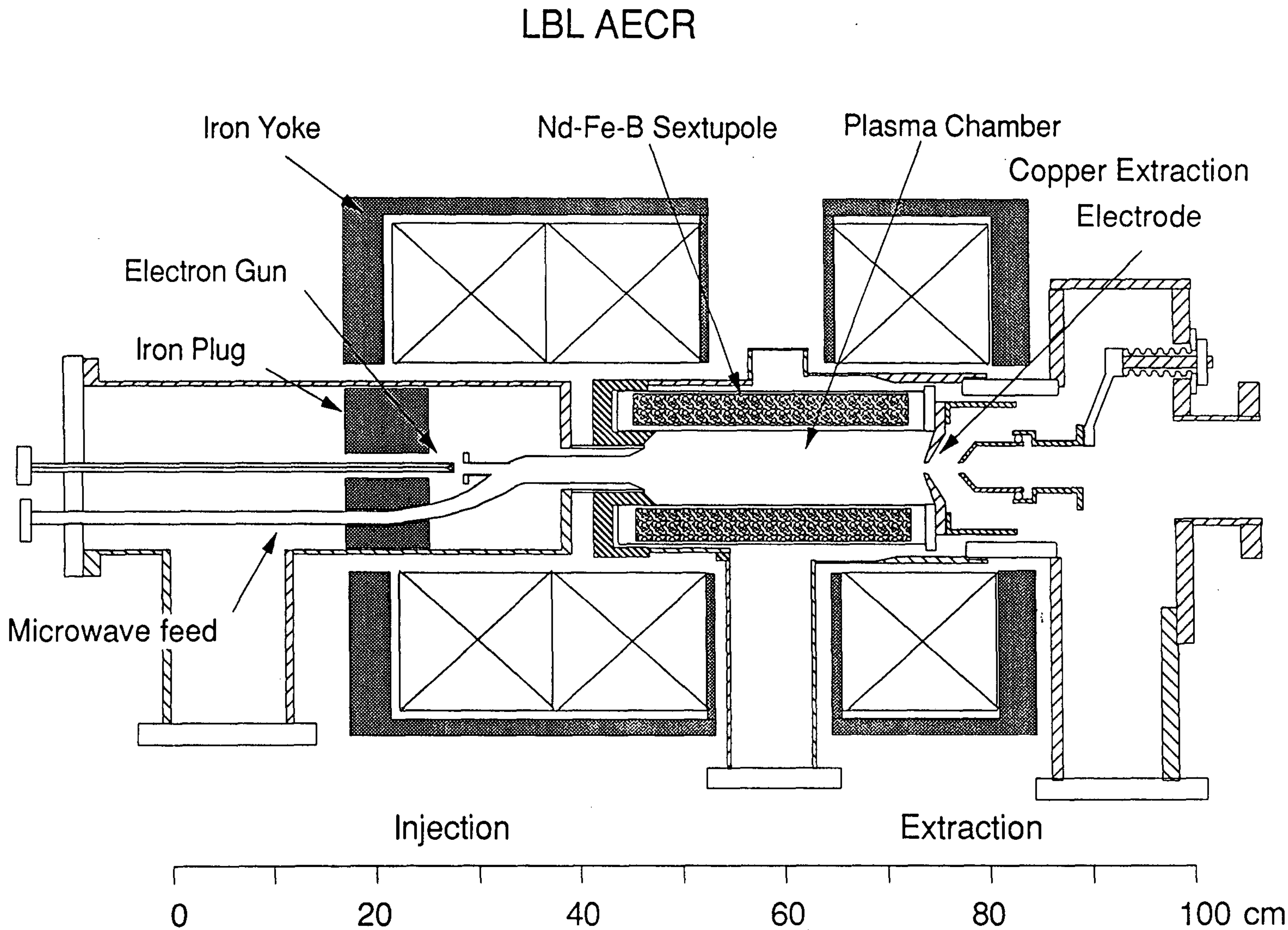

Fig. 1. Schematic drawing of the AECR. The magnetic field is produced by copper coils in an iron yoke. The iron plug on the injection side was added to increase the axial magnetic field. Electrons from a LaB_6 filament flow along the axial magnetic field lines into the plasma chamber.

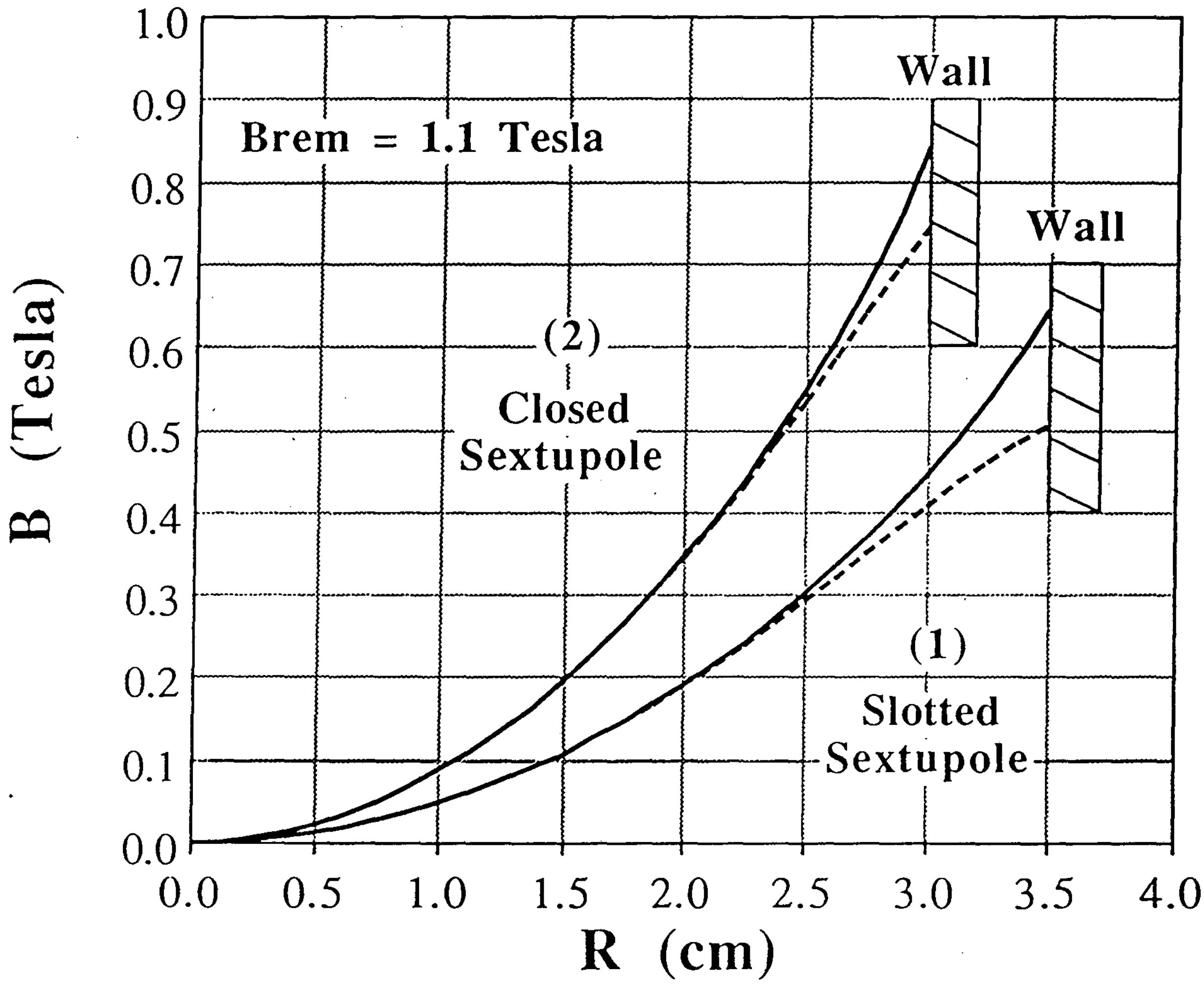

Fig. 2. Two radial field profiles are shown for the AECR. The solid lines show the pole field strength and the dashed lines show the gap field intensity between two adjacent sextupole bars. (1) indicates the case of the plasma chamber with an ID = 7.0 cm (slotted sextupole) and a maximum field of 0.64 Tesla at the chamber wall. (2) illustrates the case of the smaller chamber of ID = 6.0 cm (closed sextupole) and the maximum field strength is increased to 0.84 Tesla.

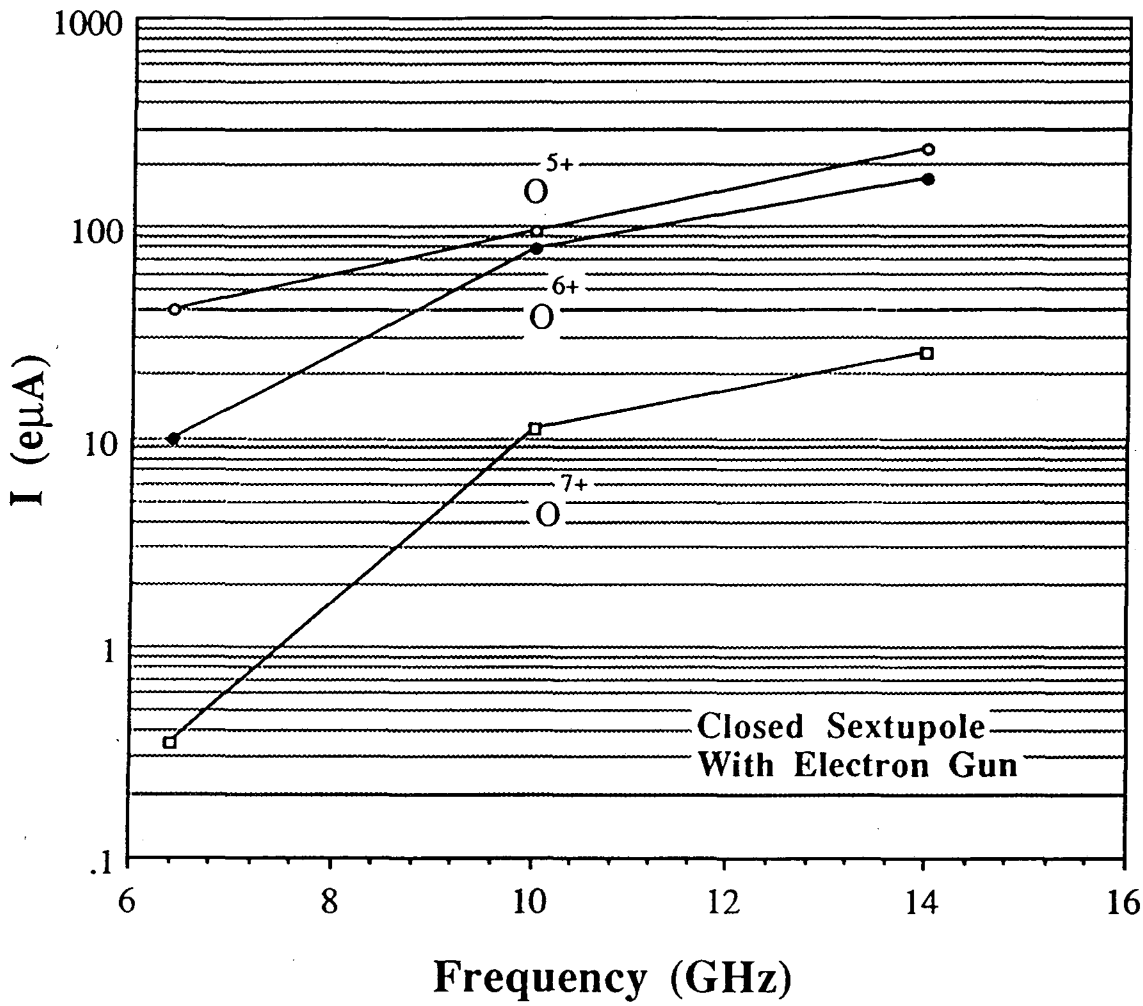

Fig. 3. High charge state oxygen ions produced by the AECR with the closed sextupole magnet and cold electron injection at 6.4, 10, and 14 GHz.

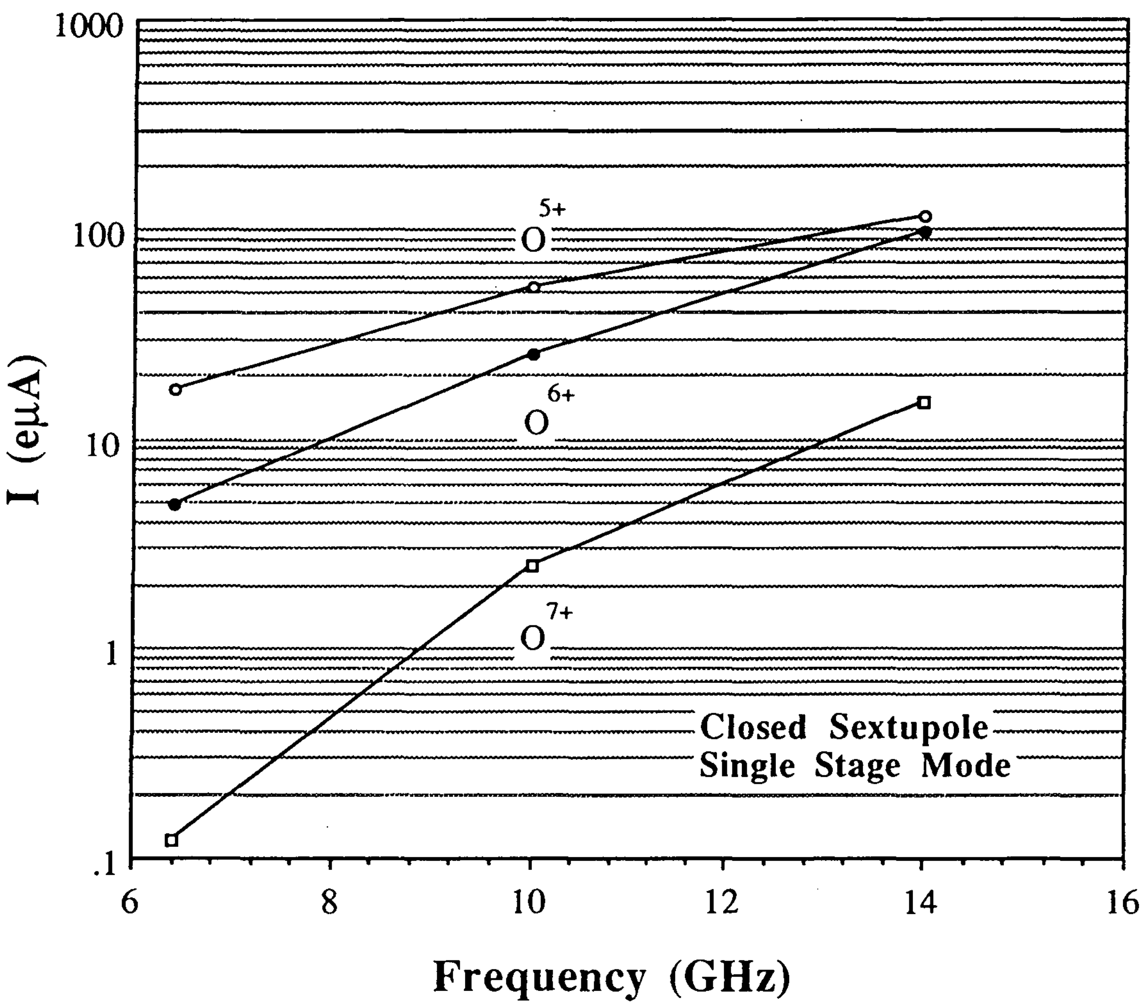

Fig. 4. High charge state oxygen ions produced by the AECR with the closed sextupole magnet operated at a single stage mode at 6.4, 10, and 14 GHz.

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