MICROWAVE DRIVEN NEGATIVE ION SOURCES

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Abstract

The efficiency and the reliability of a simple microwave-driven ion source have been exploited to generate negative ion beams for injection into the Tandem Accelerator Superconducting Cyclotron facility at CRL. In a preliminary demonstration 0.28 μA of $^4He^+$, 1.0 μA of $^{16}O^{6+}$ and 0.020 μA of $^{18}O^{5+}$ from unenriched feed have been accelerated through the tandem and 0.014 μA of $^3He^{++}$ have been accelerated through the cyclotron via the tandem.

Introduction

During the last few years, a simple microwave-driven proton source [1-3] developed at the Chalk River Laboratories (CRL) of AECL Research has become the preferred injector for high-current cw accelerator applications [4,5]. More recently, the efficiency and the reliability of the technology have attracted the interest of negative ion beam users. Specifically, the development of a dc microwave-driven negative ion source for the Tandem Accelerator Superconducting Cyclotron (TASCC) facility [6] at CRL has been initiated.

The design and the performance of the microwave-driven proton source have been extended in several respects. The production of high-current beams of heavy ions has been demonstrated. An oven has been introduced so that ion beams can be generated from nonvolatile feeds. Negative ion beams have been created by adding a charge exchange canal. The size of the ion source has been dramatically reduced by substituting permanent magnets for the solenoids that previously supplied the requisite axial magnetic field. Finally, the entire system has been operated in conjunction with the TASCC facility.

Heavy Ions

The proton source [1], designed to generate a beam current of 90 mA dc at an extraction voltage of 50 kV, is depicted in Fig. 1. The plasma chamber is a stainless steel cylinder, with an aluminum nitride window at one end, to admit 2.45 GHz microwaves, and a copper plasma electrode, with a 5 mm diameter aperture for ion beam extraction, at the other end. A uniform magnetic induction of 92 to 93 mT is generated along the entire axis of the plasma chamber by two solenoids. The extraction configuration is a triode, with an acceleration gap of 5 mm and a deceleration gap of 2 mm. The principles of the operation of the source are discussed in Ref. 2.

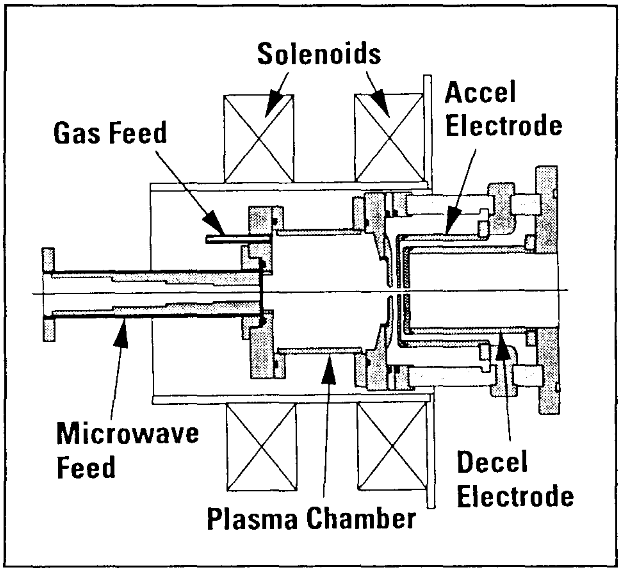

Fig. 1 Original microwave-driven CRL proton source.

Various gaseous feeds were introduced into the plasma chamber via a line adjacent to the microwave window to demonstrate heavy-ion operation. In every case, the extraction voltage was the 20 kV preferred for TASCC injection. The gas flow was adjusted for quiescent operation and the microwave power was varied to give minimal ion-beam divergence.

The corresponding beam currents and rms normalized emittances, measured as described in Ref. 7, are presented in Table 1. In every case, the ion beam consisted almost exclusively of singly-charged ions with higher charge states comprising, at most, 10% of the ion beam. The atomic fraction for the diatomic feeds, hydrogen and oxygen, was typically 70% with boron nitride liners suppressing atomic recombination [1]. The beam current was approximately proportional to the inverse square root of the effective mass. In other words, the perveance was virtually constant.

TABLE 1
Characteristics of Positive Ion Beams

Feed Gas	Effective Mass (amu)	Beam Current (mA)	Emittance (π mm mrad)
H_2	1.7	23	0.078
He	4	9.5	0.062
O_2	26	6.2	0.018
Ar	40	3.4	0.013
Kr	84	1.9	0.0084
Xe	131	1.8	0.0065

Nonvolatile Feeds

After the ion source had been operated successfully with heavy ions, the modifications illustrated by Fig. 2 were introduced to accommodate nonvolatile feeds. A simple oven consisting of a boron nitride crucible and a tantalum heating coil was mounted on the side of the plasma chamber. Two nested stainless-steel liners were installed inside the plasma chamber, to limit the condensation of the feed. Although only an 8 mm diameter aperture was open adjacent to the plasma electrode to permit ion beam extraction, the entire diameter was exposed at the microwave window to ensure good coupling of the microwaves into the plasma.

Initially, a stable plasma was established with argon. The liners were heated by the plasma to about 450°C. Subsequently, the nonvolatile feed was vaporized by gradually increasing the oven temperature to, at most, 700°C. Most of the experiments with nonvolatile feeds were conducted with bismuth, which was of particular interest for TASCC applications. Typically, with a total beam current of 5 mA, 10% of the ion beam was $\mathrm{Bi^+}$. An extended run was terminated after 16½ hours by a power supply failure. The feed-consumption efficiency of about 5% could probably be increased significantly with improved liners and by operating at higher plasma densities.

One of the principle concerns in operating a microwave-driven ion source with nonvolatile feeds is condensation of the feed on the microwave window. A conducting film would constitute a short that would prevent the microwaves from entering the plasma chamber. However, a 2 cm diameter region at the centre of the microwave window invariably was found to remain clear, as long as a stable plasma was maintained in the plasma chamber.

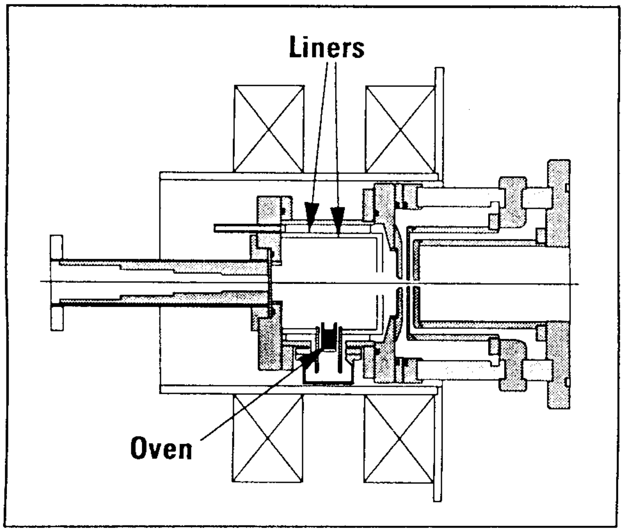

Fig. 2 Ion source modified for nonvolatile feeds.

Charge Exchange

Following the generation of substantial beam currents of positive ions from both gaseous and nonvolatile feeds, the ion source was prepared for the production of negative ions by adding a potassium-vapour charge-exchange canal as shown in Fig. 3.

The system was tested with helium and oxygen feeds. The performance is summarized in Table 2. The charge-exchange efficiencies are consistent with those reported elsewhere [8,9], despite an increase in beam current of approximately an order of magnitude.

TABLE 2
Characteristics of Negative Ion Beams

Ion	Energy (keV)	Current (μA)	Efficiency (%)
$\mathrm{He^-}$	10	8	3.5
$\mathrm{He^-}$	25	33	1.0
$\mathrm{O^-}$	20	300	25

The rms normalized emittance of the $\mathrm{O^-}$ beam was 0.0096 π mm mrad, which is considerably less than the value reported in Table 1 for an $\mathrm{O^+}$ beam. The reduction is almost certainly attributable to the relatively small acceptance of the charge-exchange canal.

Permanent Magnets

Although the microwave ion source with the charge-exchange canal had generated useful beam currents of negative ions, the large size and the high power consumption of the solenoids inhibited installation of the system on the high-voltage deck of a tandem accelerator. An array of NdFeB permanent magnets that approximated the optimum magnetic-field configuration was developed. The revised configuration is shown in Fig. 4. The magnetic induction on the axis of the plasma chamber is plotted in Fig. 5. The reliability of the ion source was also increased by replacing the o-ring sealed microwave window with a brazed assembly.

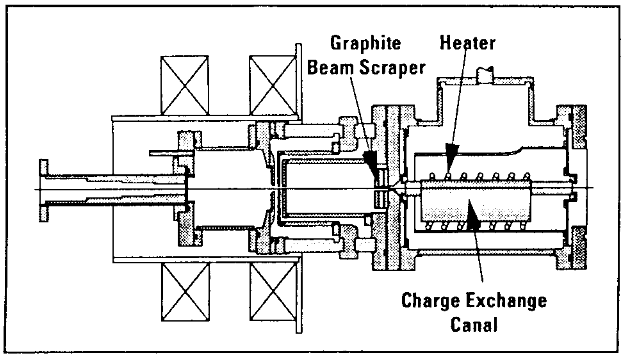

Fig. 3 Ion source with charge-exchange canal.

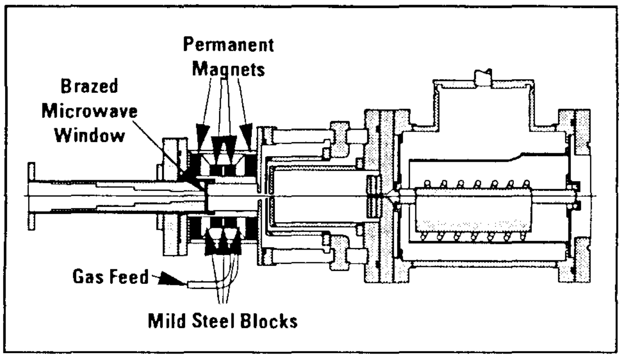

Fig. 4 Permanent-magnet microwave-driven ion source.

The permanent-magnet version of the ion source was exercised extensively on a test stand with both positive and negative ions. With the exception of a significant reduction in microwave-power efficiency, the performance was essentially unchanged. The lower efficiency is probably attributable to the substantial decline in the magnetic induction between the microwave window and the plasma electrode.

TASCC Demonstration

The system was subsequently installed on a high-voltage deck of the TASCC facility. Its performance during a preliminary demonstration is presented in Table 3. The $^{4}\mathrm{He}^{-}$, $^{16}\mathrm{O}^{-}$ and $^{18}\mathrm{O}^{-}$ ion beams were accelerated only through the tandem accelerator. The $^{3}\mathrm{He}^{-}$ ion beam was accelerated through both the tandem accelerator and the superconducting cyclotron. The $^{18}\mathrm{O}^{-}$ ion beam was generated with unenriched feed. In most cases, the negative ion beam injected into the tandem accelerator had to be limited by slits.

TABLE 3
Results of TASCC Demonstration

Input Ion	Output Ion	Input Current (μA)	Output Current (μA)	Output Energy (MeV)
$^{3}\mathrm{He}^{-}$	$^{3}\mathrm{He}^{++}$	3.0	0.014	150
$^{4}\mathrm{He}^{-}$	$^{4}\mathrm{He}^{+}$	2.0	0.28	19
$^{16}\mathrm{O}^{-}$	$^{16}\mathrm{O}^{6+}$	1.0	1.0	83
$^{18}\mathrm{O}^{-}$	$^{18}\mathrm{O}^{5+}$	0.020	0.020	63

Conclusions

It has been demonstrated that a microwave-driven ion source is a viable injector for a tandem accelerator. The permanent-magnet ion source is being redesigned for greater microwave efficiency, reduced size and increased serviceability. The ion source will be coupled via a magnetic lens to a recirculating charge-exchange canal capable of handling media such as rubidium, cesium and magnesium, which, for some ion beams, have higher charge-exchange cross-sections than the potassium vapour used in the experiments described above.

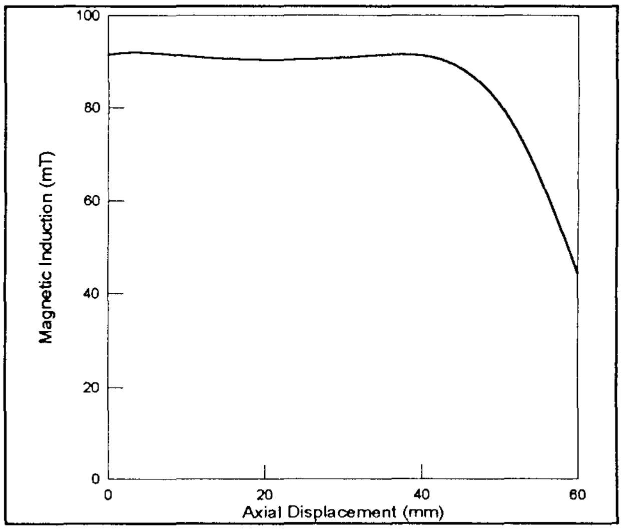

Fig. 5 Magnetic induction on axis of permanent-magnet plasma generator with origin at microwave window.

Meanwhile, an investigation of the possibility of direct extraction of negative ions from a microwave plasma generator has been undertaken.

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