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ABSTRACT

A 2.45 GHz microwave-driven ion source, originally developed to generate high-current proton beams, has been adapted to serve as a universal negative-ion injector for the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at Chalk River. Positive heavy-ion currents from the source are converted into negative currents by means of a charge-exchange canal. So far, beams of $^4He^-$, $^{16}O^-$, and $^{18}O^-$ have been accelerated through the TASCC Tandem and $^3He^-$ and $^{209}Bi^-$ beams were accelerated through both the TASCC Tandem and cyclotron. A production version of the source has been designed, with emphasis on compactness and serviceability.

INTRODUCTION

Over the last few years, the microwave-driven proton source [1-3] developed at the Chalk River Laboratories of AECL has proven to be an efficient and reliable injector for high-current cw accelerator applications up to 90 mA [4,5]. This success has led us to investigate the potential of the source for the production of heavy ion beams for TASCC [6]. Since the Tandem accelerator requires negative beams, the positive beams extracted from the source have to be converted to negative beams via a suitable charge-exchange canal [7]. Initial results were very promising. Subsequently, we have miniaturized the source in order to facilitate its installation on the injector deck of the Tandem accelerator. The source volume was shrunk and the bulky solenoids were replaced by a permanent magnet array. The miniaturization had no detrimental effect on source performance.

SOURCE OPERATION WITH HEAVY IONS

The original proton source, designed to generate a proton 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 to admit 2.45 GHz microwaves. A copper plasma electrode with a 5 mm diameter aperture is used for ion beam extraction. The extraction configuration is a triode with an acceleration gap of 5 mm and a deceleration gap of 2 mm. Two solenoids generate a reasonably uniform magnetic field of about 93 mT along the axis of the plasma chamber. The principal of the operation of the source is discussed in Ref. 2.

To investigate the suitability of the source for operation with heavy ions, various gases were introduced into the plasma chamber through a line which ends adjacent to the microwave window. To avoid long conditioning periods and to duplicate TASCC injection conditions, the extraction voltage was limited in these tests to 20 kV (the column has operated reliably at up to 50 kV). Table 1 shows beam currents and rms normalized emittances, measured under these conditions at the Chalk River ion source test stand [8]. The source worked equally well for all beams listed. As was expected, the source output dropped, under otherwise constant conditions, approximately with $m^{-1/2}$, where m is the effective mass of the extracted ion beam. By comparison to the intensities of negative ion beams usually available for injection into the Tandem, typically 1-100 μA, the positive ion currents listed in Table 1 are considered copious.

TABLE 1
Characteristics of Positive Ion Beams Measured on the Chalk River Ion Source Test Stand, with the Ion Source Shown in Fig. 1

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

THE PERMANENT MAGNET ARRAY

After it was established that the source was capable of producing heavy ion beams, the first modification we introduced was to replace the solenoids with a permanent magnet array. To minimize the size of this array, we redesigned the plasma chamber, substantially reducing its size. The revised configuration is shown in Fig. 2. The axial magnetic field profile produced by the permanent magnet array is shown in Fig. 3. Over most of the source volume, the magnetic field is homogeneous to within 5%. However, over the last 2 cm approaching the extraction aperture, the field drops off by a factor of 2. This is an unintended design feature, caused by our decision to retain the original (proton source) extraction column.

The permanent-magnet version of the microwave ion source was tested extensively on the Chalk River ion source test stand. With the exception of a significant reduction in microwave power efficiency, the performance was essentially unchanged from that of the solenoid source. We attribute the lower efficiency to the decrease in the magnetic induction in the vicinity of the plasma electrode.

This source was then equipped with an external oven and an internal electrically heated liner for the production of beams from non-volatile materials. Our development effort concentrated on the production of Bi beams in response to a requirement from researchers at TASCC. A 2 mA mixed Xe/Bi beam was extracted from the source, again at 20 kV extraction voltage, with a Bi^+ fraction of 70%. The Bi consumption rate was 16 mg/hr.

CHARGE EXCHANGE

Following the proof of principle that substantial beam currents of positive heavy ions from both gaseous and non-volatile feeds can be produced, the permanent-magnet ion source was coupled to a charge-exchange canal. The resulting production of negative ions is summarized in Table 2. The charge exchange efficiencies are consistent with those reported elsewhere [9,10]. The rms normalized emittance of the O^- beam was measured to be 0.0096 π-mm-mrad.

TABLE 2
Characteristics of Negative Ion Beams Generated by the Permanent-Magnet Ion Source (shown in Fig. 2) Coupled to a Charge-Exchange Canal

Ion	**Energy (keV)**	**Current (μA)**	**Charge Exchange Efficiency (%)**
He^-	10	8	3.5
He^-	25	33	1.0
O^-	20	300	25
Bi^-	19	21	5

The measured intensities of negative beams were lower than expected because of two deficiencies. First, a slight mismatch of the permanent magnets caused a residual transverse field of approximately 30 Gauss near the extraction electrode. This field steered the extracted positive-ion beam off axis, resulting in loss of about 50% of the beam on the defining aperture ahead of the charge-exchange canal. Second, the charge-exchange canal was located downstream of the beam waist and the canal aperture intercepted some beam. In all, the transmission of the canal was only 20%. Despite these limitations (which in principle can easily be addressed) the source/charge-exchange-canal combination generated substantially higher negative-ion beam currents than could be extracted from our conventional ion sources during tests at TASCC.

ON-LINE DEMONSTRATION

The permanent-magnet ion source, followed by the charge-exchange canal, provided negative-ion beams for the TASCC facility during two test runs. The results are summarized in Table 3. The $^{4}He^{-}$, $^{16}O^{-}$ and $^{18}O^{-}$ ion beams were accelerated through the Tandem accelerator. The $^{3}He^{-}$ and $^{209}Bi^{-}$ ion beams were accelerated through both the Tandem accelerator and the superconducting cyclotron. The $^{18}O^{-}$ beam was generated from a natural O_2 feed (^{18}O has a natural abundance of 0.20%). In most cases, the negative-ion beam injected into the Tandem was limited by the Tandem's acceptance slits.

TABLE 3
Results of TASCC Demonstration

Injected Ion	Final Accel-erated Ion	Injected Current (µA)	Tandem Output Current (µA)	Cyclotron Output Current (µA)	Output Energy (MeV)
$^{3}He^{-}$	$^{3}He^{++}$	3.0	1.4	0.014	150
$^{4}He^{-}$	$^{4}He^{++}$	2.0	0.28	-	19
$^{16}O^{-}$	$^{16}O^{6+}$	1.0	1.0	-	83
$^{18}O^{-}$	$^{18}O^{5+}$	0.020	0.020	-	63
$^{209}Bi^{-}$	$^{209}Bi^{23+}$	6.0	0.340	0.040	1128

THE COMPACT PERMANENT-MAGNET SOURCE

Following these tests, the permanent-magnet source was further modified for greater microwave efficiency and improved serviceability. The resulting configuration is shown in Fig. 4. The field distribution of the new quasi-solenoidal magnet array more closely resembles the flat axial profile of the original solenoid source. The multi-polar design of the array is expected to be less prone to generating transverse field components that limit the performance of the present version. The magnets are mechanically separated from the body of the plasma generator which improves the serviceability of the source. A brazed aluminum nitride window will replace the troublesome O-ring seal assembly. This source is being fabricated at present. Also under construction is a new charge-exchange canal, with a larger aperture for increased beam transmission.

CONCLUSIONS

Intense negative-ion beams generated from gaseous and non-volatile feeds have been produced from a permanent-magnet source coupled to a charge-exchange canal. Charge-exchange efficiencies similar to those reported in the literature have been achieved. Experience gained during recent runs at the TASCC facility has been incorporated into the design of a new source intended for routine use at TASCC.

We are also investigating the possibility of direct extraction of negative ions from the microwave-driven plasma generator.

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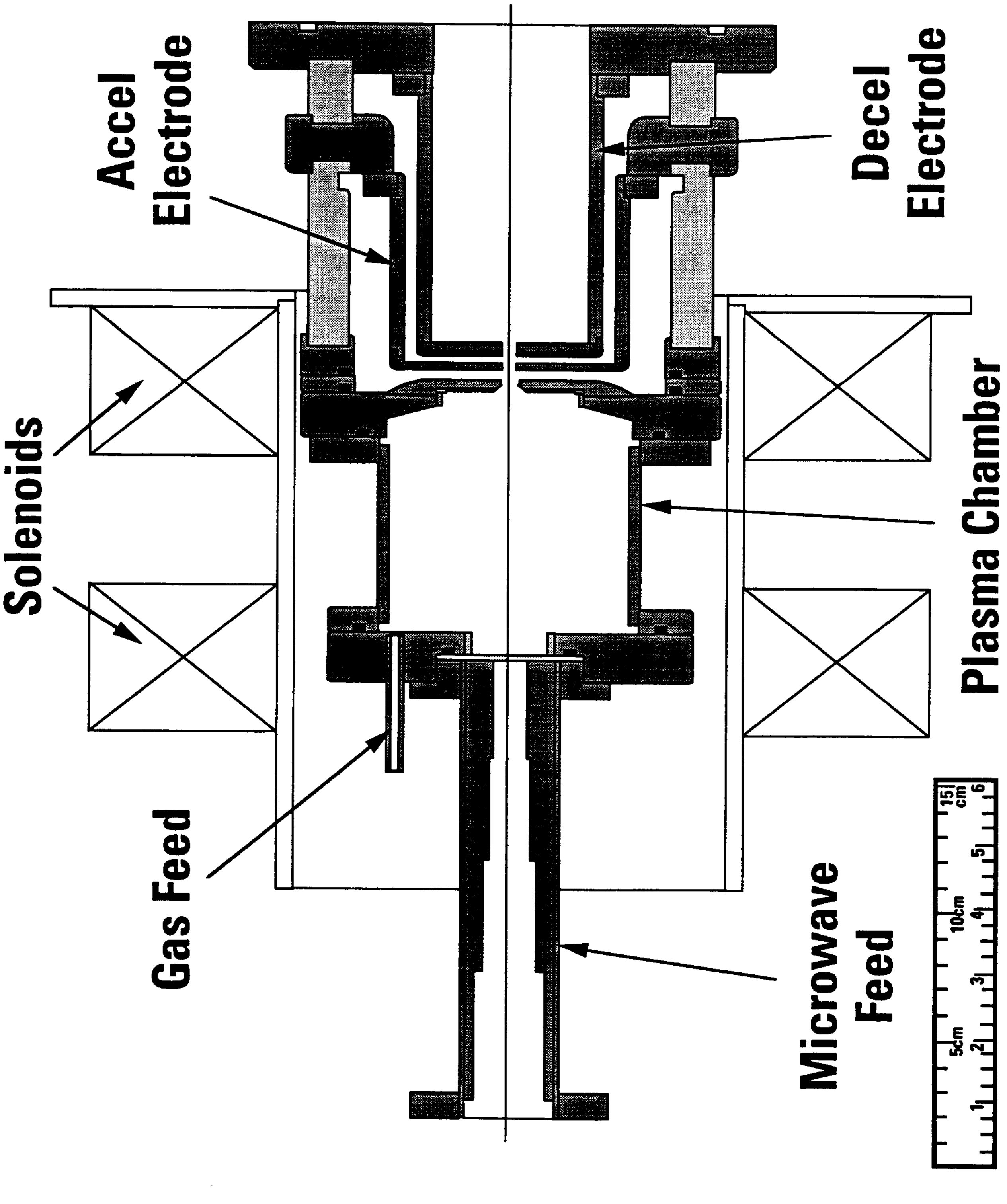

Fig. 1   Microwave-Driven Chalk River Proton Source

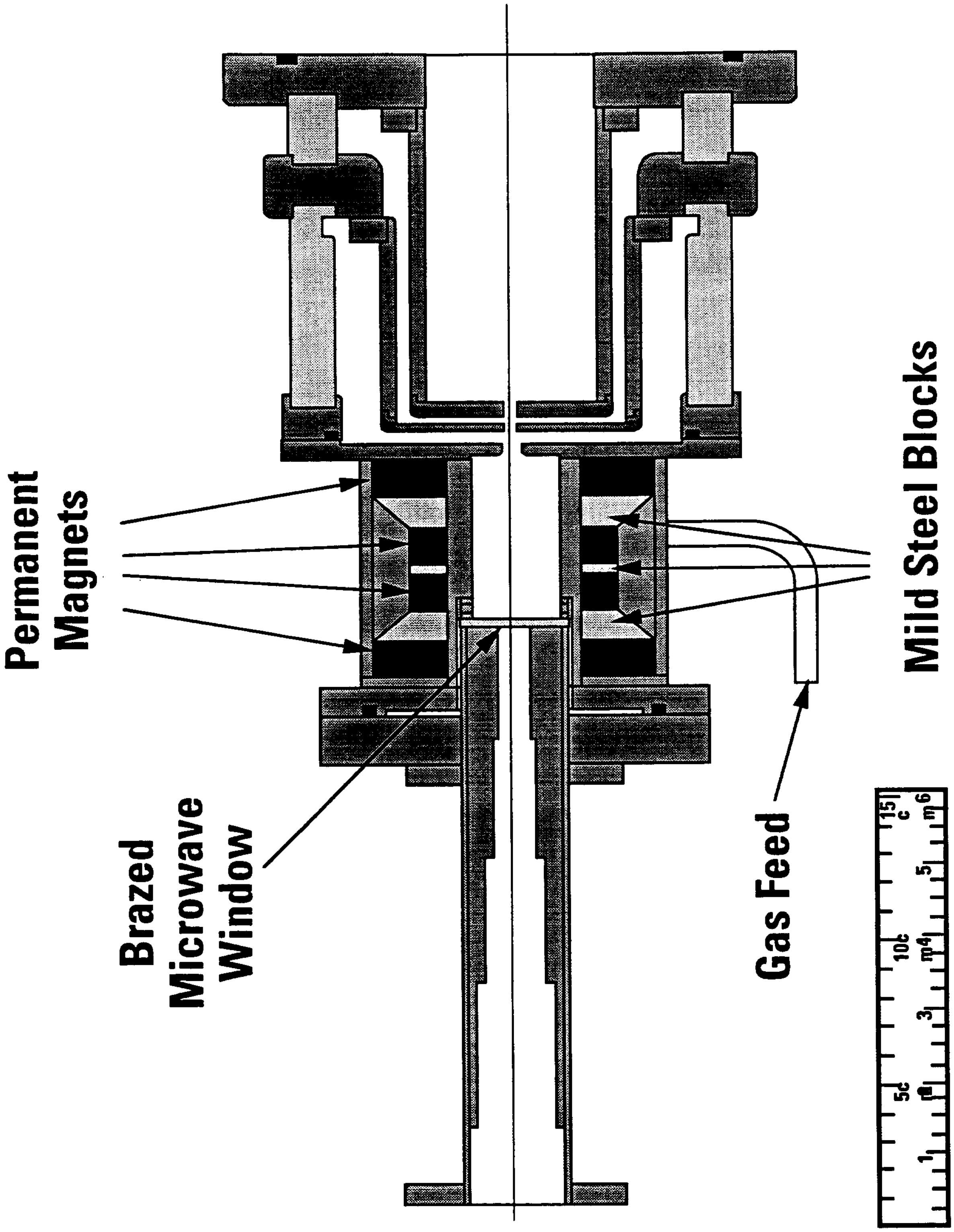

Fig. 2   Permanent-Magnet Microwave-Driven Heavy Ion Source

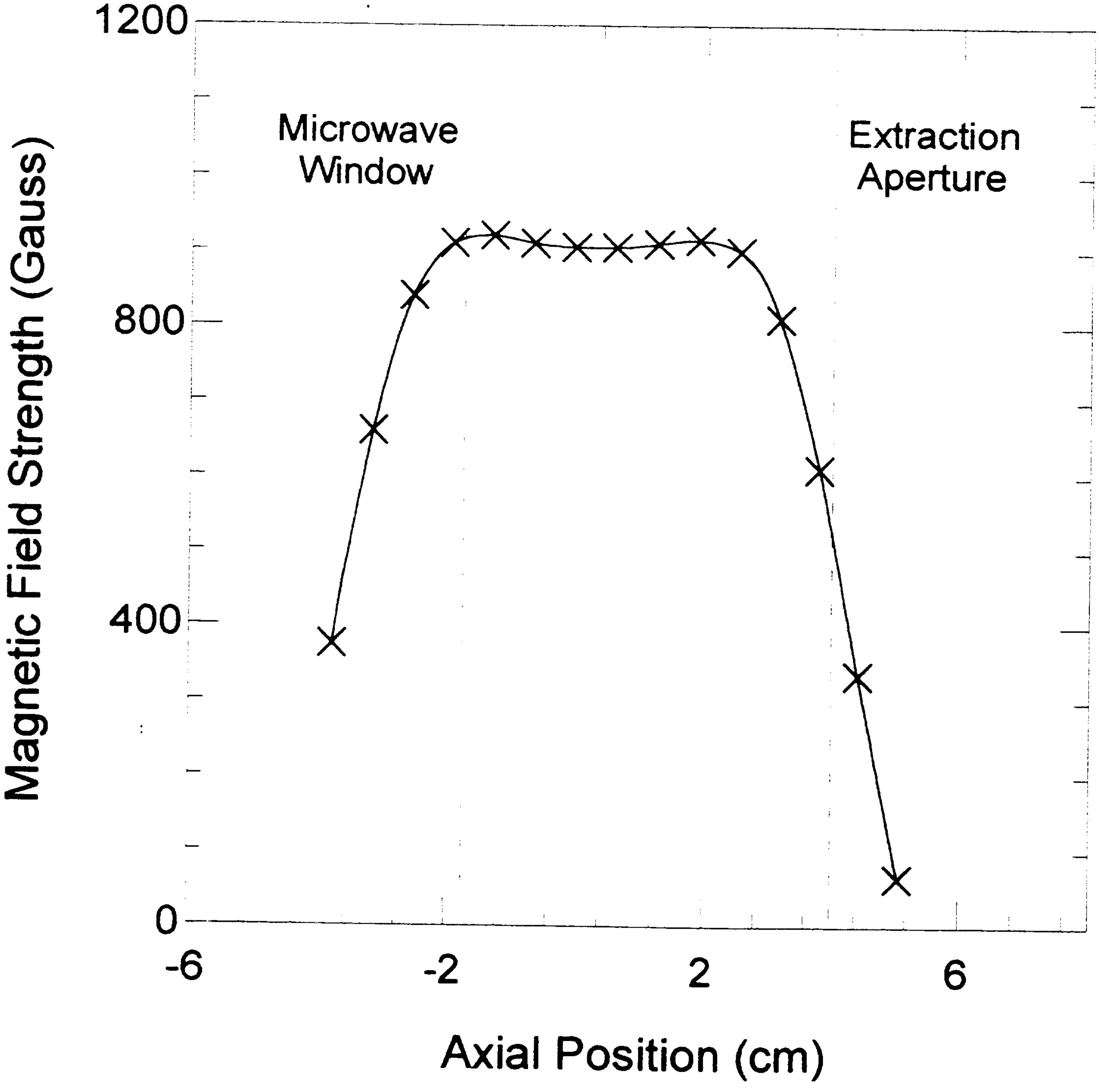

Fig. 3 Axial Magnetic Field Profile of Permanent-Magnet Heavy Ion Source

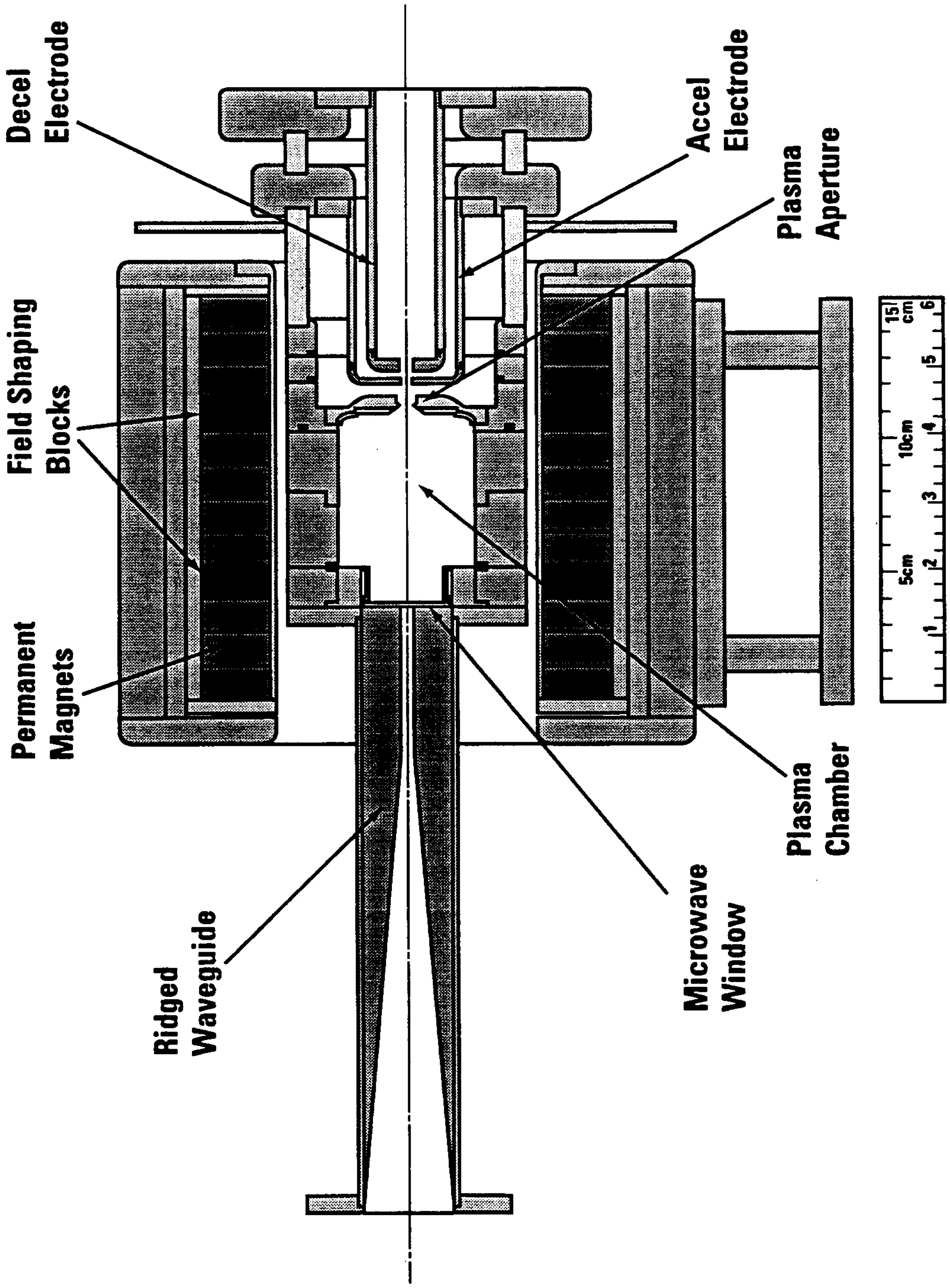

Fig. 4   Compact Permanent-Magnet Microwave-Driven Ion Source