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Summary

A dc negative hydrogen and/or deuterium ion source is needed to produce high-power, high-energy neutral beams for alpha diagnostics and current drive applications in fusion devices. The favorable beam particle energy for such applications extends to 1.5 MeV/amu. Continuous-wave (cw) radio-frequency quadrupole (RFQ) accelerators have been proposed to accelerate negative ions efficiently to this energy range. In this paper, the desired beam properties for ion beams injected into cw RFQ accelerators are summarized. A number of candidate ion sources being developed at Culham, JAERI, LBL, and ORNL may prove useful for these applications. The properties of the Volume Ionization with Transverse Extraction (VITEX) ion sources being developed at ORNL are presented. Scaling such a dc ion source to produce ampere beams is discussed.

1. INTRODUCTION

In the last decade, much progress has been made in extending the parameters of fusion plasmas toward the conditions required for ignition. The tokamak is the leading concept among magnetic confinement schemes, and the operation of major tokamak devices (such as ASDEX, DIII-D, JET, JT-60, T-15, and TFTR) is providing increased understanding of hot plasmas and improved plasma confinement. Recent achievements in tokamak experiments[1] include ion temperatures of ≈20 keV, a fusion figure of merit (product of deuteron density, energy confinement time, and ion temperature) of $\approx 2 \times 10^{14}$ cm^{-3}·s·keV, and high plasma power density with a beta value of about 5%. These advances support the pursuit of breakeven experiments (in which total fusion energy production equals total energy input) in planned ignition devices such as the Compact Ignition Tokamak (CIT).[2]

One objective of the CIT is the cost-effective production of a burning deuterium-tritium (DT) plasma for the study of alpha particle effects and physics issues of tokamak burning plasmas. Among the key physics issues are confining the energetic alpha particles, confining reactor-relevant plasmas, and controlling the profiles, thermal excursions, and composition of burning plasmas. Reliable, proven diagnostic techniques for measuring the behavior of high-energy alpha particles in tokamaks will be needed to support this work.[3] Neutral beam diagnostics are being considered for measuring the temporal, spatial, and velocity distributions of confined alphas.[4–6] Basically, a beam of neutral atoms is injected into the plasma, allowing single or double charge-exchange interaction with a confined alpha. Spectroscopic measurements of characteristic lines emitted from the excited helium ions and energy measurements of escaped neutral helium can be used to characterize the confined alphas. Neutral beam systems for this application have been proposed.[7–9] Negative ion sources that can produce hydrogen and/or deuterium beams at 40–100 keV and 1.0 A (as described in Table 1) are needed to provide the input to the postacceleration components that will produce beam energies of about 1 MeV/amu for a single charge-exchange application. [Studies of the confined alpha distribution require higher-Z beams (such as lithium) for double charge exchange.]

Engineering test reactors for long-pulse, integrated tests of fusion physics and technology are being studied (e.g., INTOR, NET in Europe, FER in Japan, OTR

Table 1. Injector requirements

	Current drive	Alpha diagnostic
Ion source		
Ion	D^-	H^-
Current, A	1.5	1
Energy, keV	40–100	40–100
Diameter, cm	7–14	7–14
Current density, mA/cm^2	20–80	20–80
Normalized rms beam emittance, π·cm·mrad	0.05	0.05
Gas load, torr·L/s	20	20
Pulse length, s	dc	3
Ion temperature, eV		
20 mA/cm^2	0.37	0.37
40 mA/cm^2	0.75	0.75
80 mA/cm^2	1.5	1.5
LEBT		
Output current, A	1.2	0.9
Normalized rms beam emittance, π·cm·mrad	0.05	0.05
Exit pressure, torr	2×10^{-5}	2×10^{-5}
Length, cm	100	100
Area of cryopumps, cm^2	1×10^5	1×10^5

in the U.S.S.R., and FED and TIBER in the U.S.). The projected long-pulse to steady-state operation creates a requirement for noninductive plasma current drive.[10] Various techniques have been proposed,[11–15] including injection of energetic particle beams; launching of RF waves, including lower-hybrid, high-frequency fast waves and low-frequency fast waves; hybrid schemes that combine RF and/or beam methods; and other schemes (e.g., alpha particle and intense synchrotron radiation drive approaches).

For current drive via neutral beam injection, the injected neutrals are converted into fast ions via collisions with the background plasma. These fast ions circulate around the torus, interact with the electrons of the background plasma, and thus create a substantial toroidal current. This beam current idea was first proposed by Ohkawa[16] and has been demonstrated on various tokamaks.[1,17] At ORNL, we are pursuing technology development of high-power neutral beams for efficient non-inductive current drive in future fusion reactors.[18] A study has been initiated[19] to identify the beam parameters for optimum current drive efficiency. Early calculations suggest that multi-megaelectron-volt beams of deuterium are needed to penetrate reactor plasmas and produce the desired plasma core current drive. When combined with an edge current drive method (e.g., a lower hybrid scheme), plasma core current drive should make it possible to obtain the current profile required for stable operation.

Neutral beam injectors for current drive applications[20] need ion sources that can produce high-current, negative deuterium ion beams that will be accelerated to 1–3 MeV. High-current RFQ accelerators have been designed[21] to produce cw ion beams with energies of up to 3 MeV, currents of up to 1.2 A, and a beam radius of 2.5 cm. An RF plasma neutralizer, 15 cm in diameter and 2 m long, is being considered for converting fast ions into neutrals.[22] Ion sources for these RFQ accelerators must produce 1.5-A negative deuterium ion beams at 40-100 keV. For accelerator electrodes with a geometrical transparency of 50%, the negative ion current density inside the source is 40 mA/cm^2, uniformly distributed over a 10-cm-diam extraction plane. The ion temperature limit is 0.75 eV. Other requirements, such as gas load and pressure, are listed in Table 1, which specifies the basic parameters of the source and the low-energy beam transport (LEBT) system. To minimize premature neutralization of beam ions in both the LEBT and the RFQ accelerator, a pressure of 2×10^{-5} torr at the LEBT exit is a crucial parameter. Thus, an ion source with high gas efficiency is essential for this application.

Negative ions can be produced by volume excitation and ionization, by surface conversion, or by charge exchange. Volume production is the most favorable for producing negative ions at ion temperatures well below 1 eV (Ref. 23). Volume-produced negative ion sources are being developed worldwide;[24–33] although no existing source can fulfill all of the requirements listed in Table 1, many have potential for scaling up to these requirements. We present the source operation and beam properties of VITEX sources[27,31] and discuss the scaling of these sources to current drive and alpha diagnostic applications.

2. VITEX ION SOURCES

Neutral beam injection has proved to be an effective way to heat plasmas in magnetic confinement fusion devices.[34–36] For application to fusion reactors, the desired particle energy of neutral beams is as high as 1.5 MeV/amu. Because the neutralization efficiency of negative ions is higher than that of positive ions at such high energies, negative-ion-based neutral beam injectors are the only viable choice for reactor applications. At ORNL, negative ion source development[37,38] has been pursued since the late 1970s. We are now devoting our efforts to the development of the VITEX ion source.[27,31,39] The characteristics of this source are similar to those published elsewhere.[40,41] We briefly describe its operation and features.

An artist's conception of a VITEX ion source is shown in Fig. 1. Figure 2 shows a schematic of a VITEX negative ion source, including the source components and

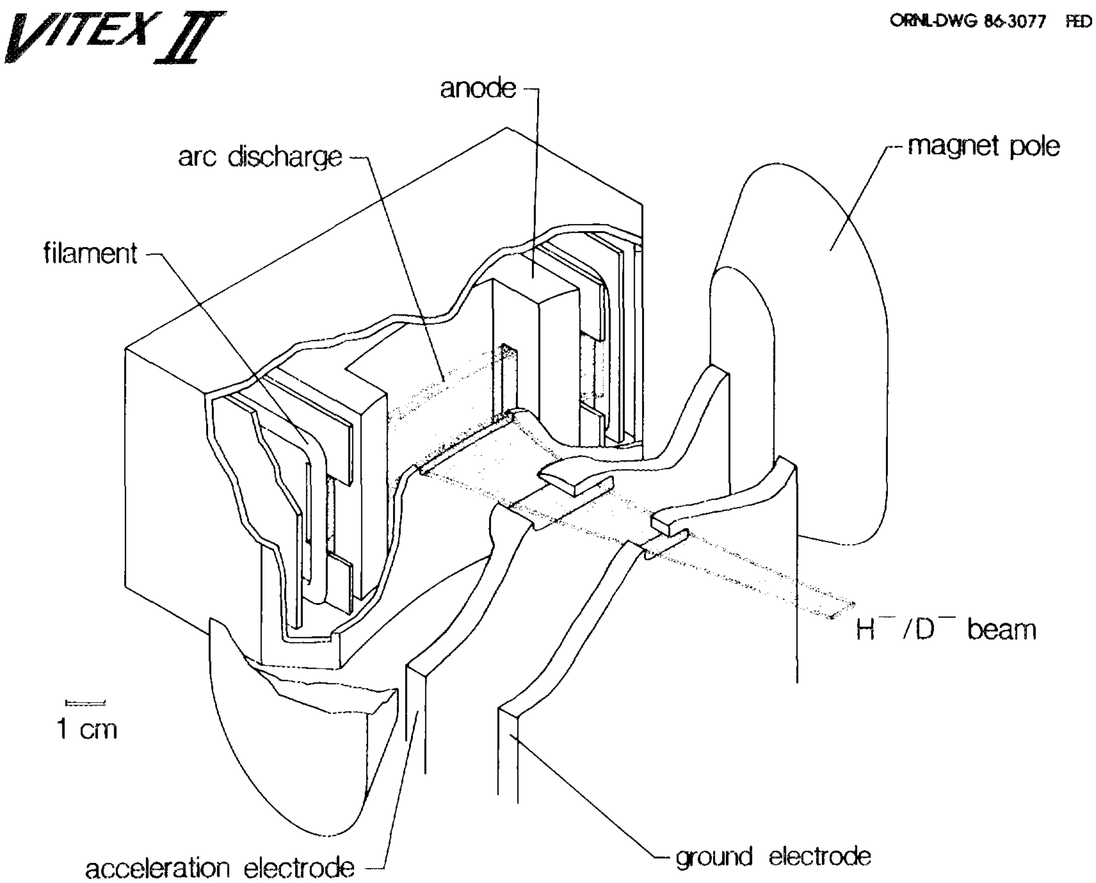

Fig. 1. Artist's conception of VITEX II ion source.

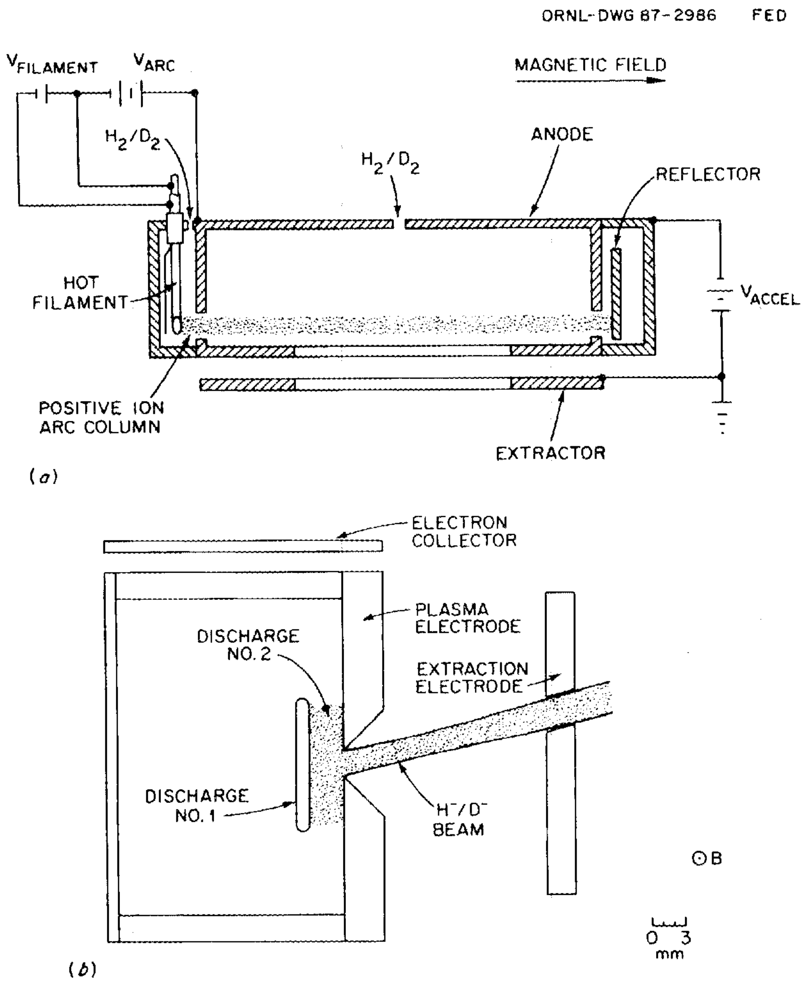

Fig. 2. Source components, including power supplies.

power supplies. Usually, these sources consist of a plasma generator, an ion accelerator, and an electron recovery electrode. In experiments to date, the plasma generator consists of a graphite arc chamber which is plasma sprayed with molybdenum. At each end of the arc chamber, a 3.5-mm-diam tantalum filament with an electron reflector plate is aligned with the anode collimation slot. A uniform magnetic field adjustable from 0.05 to 0.2 T is applied along the long dimension of the arc chamber. The other components of the plasma generator are the two anode (or arc) collimation slots, which have a 2.5- by 20-mm rectangular cross section and are 20 mm long; a water-cooled copper plate for potential control; and a biased plasma electrode with either circular or long slit ion emitting aperture. For low-energy (about 20-keV) beams, an ion extraction electrode (extractor) located 1 cm downstream of the plasma electrode is used to form ion beams. To form ion beams with energies approaching 100 keV, an accelerator with multiple electrodes[42] may be needed.

During a normal arc discharge, the tantalum filaments are heated to emitting temperature by passing a cw heating current of about 300 A through them. A cw magnetic field of about 0.12 T is applied. After the hydrogen (or deuterium) gas is fed in, the arc supply V_{arc} is turned on. Primary electrons emitted from each filament are accelerated through the anode collimation slots and reflected by the opposite filament. The oscillating primary electrons ionize gas particles with which they collide and create an intense arc column in line with the applied magnetic field. Under such intense hot cathode Penning discharges, the plasma density in the arc column can be above 10^{13} ions/cm^3.

Hydrogen molecules in the VITEX ion source are excited to high vibration levels by the energetic electrons in the arc column and by neutralization and excitation of molecular ions on the arc chamber walls. These excited molecules then collide with and attach to cold (<1-eV) plasma electrons in the second plasma volume near the extraction region, where they are converted into negative ions via dissociation attachment processes. (This consideration of plasma processes and in particular the consideration of two volumes is drawn from theoretical work by Hiskes,[43–45] in which the first volume is called chamber I and the second, chamber II.)

During normal source operation, the electrical supplies for heating the filaments, applying the source magnetic field, and recovering the leakage electrons are on continuously. The working gas (hydrogen or deuterium) can be fed in either a pulsed mode or in a cw mode. After the desired gas density is established, the arc supplies are pulsed on to establish the intense arc discharge. The extraction supply can be pulsed just before or after turning on the arc supplies. The negative ions in the extraction region next to the ion-emitting aperture of the plasma electrode will be extracted and accelerated to form an intense ion beam. Source electrons in this region will become leakage electrons and be accelerated into the extraction gap of the ion accelerator. Due to the strong crossed electric and magnetic fields in the extraction gap, the leakage electrons are separated from the extracted negative ions at a region in the extraction gap near the plasma electrode. These leakage electrons are guided and directed to the electron recovery electrode, which is biased at a potential of about 10% of the extraction voltage. Thus, the electric power wasted on the leakage electrons is minimized. The negative ion beams so formed are free of electrons. This simplifies the optics design of the ion accelerator.

Typical performance of a VITEX source is listed in Table 2. As shown in Fig. 3, experimental data reveal that the current density is a decreasing function of the area of the ion-emitting aperture. This feature could be associated with the nonuniformity of the negative ion density or with the plasma sheath. Effects of other parameters such as gas feed, negatively biased potential of the plasma grid, and the width of chamber II have been investigated and optimized for increasing negative ion output.[27,31] For instance, we observed that the current density in the

Table 2. Present and scaled VITEX negative ion source performance

	Achieved		
Parameters	Oval aperture, 12.7 × 38.1 mm	Slit aperture, 1 × 20 mm	Scaled
Ion	H^-	H^-	D^-
Energy, keV	13	18	100
Current, A	0.1	0.03	1.5
Current density, mA/cm^2	34.7	150	40
Pulse length, s	0.1–10	0.1–10	dc
Duty factor, %	>10	>10	dc
Extraction area, cm^2	2.88	0.2	40
Source pressure, mtorr	20	200	5
Gas load, torr·L/s	2.4	2.4	<20
Normalized rms beam emittance,[a] π·cm·mrad			
X	0.02	0.013	<0.05
Y	0.03	0.017	<0.05
Ion temperature, eV	<0.88	0.58[b]	0.75

[a]The negative hydrogen ion beams are 12 keV and 50 mA for the oval aperture, 14 keV and 12 mA for the slit aperture.

[b]An ion temperature of 0.12 eV was measured for low current density beams with no aberrations.

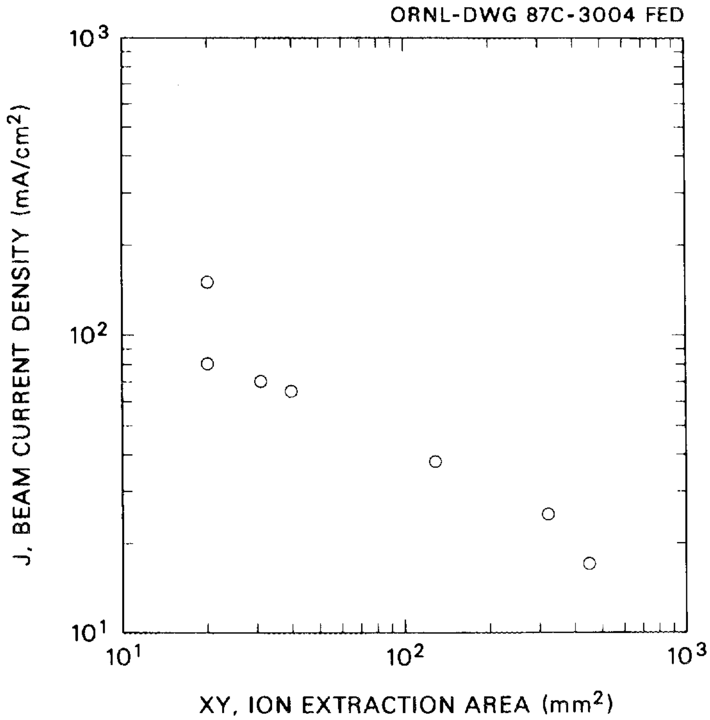

Fig. 3. Effect of extraction area on beam current density.

source can be affected by the plasma grid biasing potential. The typical measured ion temperature[46] is about 0.6 eV for VITEX negative ions. For ion beams with low current density (a couple of mA per cm^2) and low accelerator aberrations, the measured ion temperature was as low as 0.12 eV. These source characteristics must be considered in the design and development of dc high-power, multi-megaelectron-volt neutral beam injectors.

3. DESIGN CONSIDERATIONS FOR A CW NEGATIVE ION SOURCE

For a 3-MeV neutral beam with a nominal rms divergence of 1 mrad, which is reasonable for fusion applications,[20,21] the maximum limit on the system effective ion temperature is 3 eV, which corresponds to a normalized emittance of 0.05 π·cm·mrad for a beam radius of 2.5 cm. The conservation of the beam emittance implies that the ion temperature is 0.75 eV for a beam radius of 5 cm at the source. A current density of 40 mA/cm^2 at the source plasma is required to form

1.5-A D^- beams by using a 10-cm-diam extraction grid with 50% transparency, as listed in Table 1. To maintain a constant beam brightness, the system effective ion temperature limit must be proportional to the effective current density. Thus, if the current density is only 20 mA/cm^2, the ion temperature must be 0.37 eV to maintain the 1.5-A current output and 0.05-π·cm·mrad normalized emittance. On the other hand, if the current density is 80 mA/cm^2, the ion temperature can be as high as 1.5 eV. Also, a decrease of effective beam current density may result from emittance growth in the beam line components; this would create additional demands for lower ion temperature at the source. This emittance growth often occurs in the accelerator column or a downstream component of the system. The low ion temperature limit implies that the beam in the accelerator column must be round and uniform (long slits may do but would imply a plasma LEBT). For a round beam, the LEBT will be an electrostatic ring concept pursued at both ORNL[47] and LBL[48] or a plasma LEBT pursued at LANL. The requirement of low ion temperature at the ion source makes the volume negative ion source the preferred candidate for fusion applications.

As mentioned earlier, a number of the volume negative ion sources being developed in the United States and other countries may be scaled up for fusion applications. For hydrogen negative ion beams, a current density above 100 mA/cm^2 has been achieved for ion extraction apertures below 0.2 cm^2. Moreover, the geometrical transparency of a dc or long-pulse accelerator is nominally below 50%. For producing 1-A negative ion beams, the scaled source should produce negative ions uniformly over an extraction area of 20 cm^2 or larger. If the current density of negative deuterium ions is half that of the negative hydrogen ions in a volume source, as published elsewhere,[29] the extraction area of the dc negative ion source will be above 40 cm^2. The performance of such a scaled dc VITEX source is listed in Table 2.

Figure 4 is a conceptual design for a scaled dc VITEX source. The hot filament, hollow cathode type of electron feed[49] is used to create individual arc columns for each slit beamlet. A large, water-cooled plate next to the arc columns is used for plasma potential control. The plasma grid with 50% geometrical transparency could be electrically biased for the maximum negative ion output. The electron recovery

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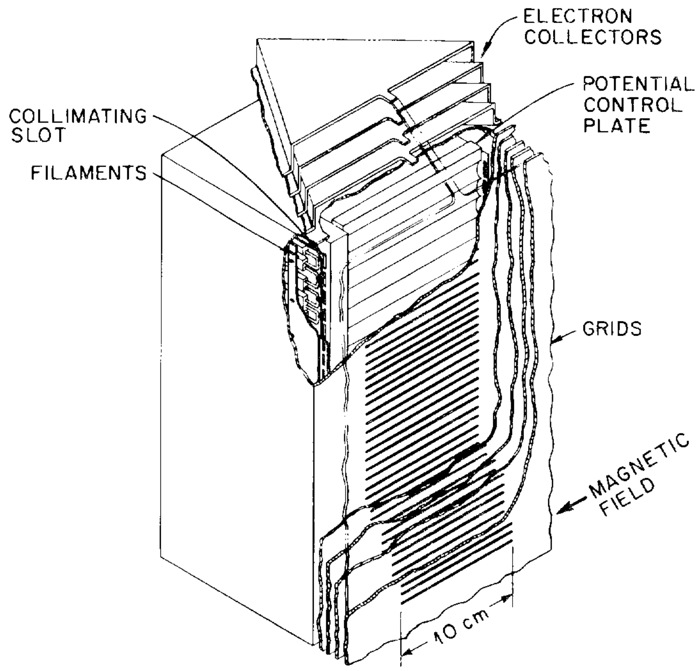

Fig. 4. Conceptual cw ampere negative ion source.

structures collect electrons that are either leaked out from the source plasma or created in the accelerator column. If the negative ion generator can produce negative deuterium ions with a current density of 40 mA/cm^2, the ion accelerator will be designed with 20 extraction slits, each 0.2 by 10 cm; 0.2 cm is transverse to the applied source magnetic field, and 10 cm is parallel to the magnetic field. The source should form 1.5-A D^- beams. A tetrode-type ion accelerator will extract and accelerate negative ions to 100 keV. With a tetrode accelerator,[50] the beam current can be varied by changing the extraction grid potential without changing the beam energy. Constant beam energy is a desired parameter for optimal performance of RFQ accelerators.[51] If positive ions must be prevented from flowing back through the accelerator or if plasma must be maintained in the LEBT for optimal beam transmission to the RFQ, the accelerator will be designed and developed with a decel electrode.

For dc operation, the lifetime of the hot filaments shown in Fig. 4 may degrade the source reliability and stability. If this is the case, the indirectly heated, hollow cathode type of electron feed used in the long-pulse positive ion source[52,53] will be used. That source produces 30-s positive hydrogen ion beams at 80 keV and 50 A. To handle a nominal gas load of 20 torr·L/s or higher, an innovative differential-pumping system between the negative ion source and the LEBT device must be developed to keep the pressure in the LEBT below 2×10^{-5} torr. For example, gas pumping around the ion source could to used to maintain the pressure in the accelerator column at <1 mtorr and the pressure in the upstream part of the LEBT section at <0.1 mtorr.

To develop a reliable and functional dc negative ion source for neutral beam current drive and alpha particle diagnostics applications to fusion reactors, the following research opportunities are envisaged.

3.1 ELECTRON RECOVERY STRUCTURES

Electrons would be formed by the charge-exchange loss of negative ions in the accelerator column. For reliable operation of the accelerator, the electrons formed in each gap may need to be collected at an electrode structure biased at 50 to 90% of the gap potential. Under normal operation, most of the electrons are produced in the upper half (closer to the source plasma) of the gap and should be guided by the crossed electric and magnetic fields toward the biased electrode structure located outside the gap and collected there. This electron recovery scheme for the source leakage electrons is similar to that currently used in the VITEX sources. But the electron collectors for the charge-exchange electrons in each accelerating gap could be located at the top of the source, as shown in Fig. 4, or at both sides of the source. This scheme has not been tested yet and should be demonstrated experimentally if the need arises in a source with a tetrode accelerator.

3.2 MULTIAPERTURE ACCELERATOR

An accelerator with multiple extraction rectangular slits or circular apertures is needed to form the desired high-current, high-quality negative ion beams for postacceleration with a cw RFQ accelerator. We need to evaluate the reliability of the source operation and to investigate and study the optical properties of beams so formed. The power loadings to the electrodes in the accelerators need to be measured so that proper cooling techniques can be used for the dc source.

3.3 NEGATIVE ION GENERATOR

Negative ion generators to be used for the dc ion source should produce a current density of about 40 mA/cm^2 of negative deuterium ions in the extraction region. The source needs to be designed, fabricated, assembled, and operated to produce ampere negative ion beams. The source components to be developed are those in the dc plasma generator. For example, the electron feed assembly must be designed and developed for cw operation. Of course, much of the ion source technology derived from the development of long-pulse positive ion sources can be used for this purpose. Also, the plasma generator must be optimized to create uniform plasma and negative ion density over the large extraction area (exceeding 100 cm^2). In addition, research and development will be devoted to increasing the current density of negative deuterium ions. The other challenge will be to improve gas efficiency and to reduce gas load.

4. CONCLUSIONS

Existing ion source technology is relatively mature for producing a dc negative ion source. The ion accelerator needs only a modest development effort to form high-quality negative ion beams and to handle harmful electrons. The critical issue is to produce dense negative ions uniformly over a large extraction area (approaching 100 cm^2). Given the fast progress of negative ion source development in recent years, we are confident that a dc VITEX source can be scaled up to produce ampere negative deuterium ion beams for future fusion reactors.

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