EXPERIMENTAL DATABASE AND DESIGN CONCEPT FOR A 1-MW, 200-keV NEUTRAL-BEAM LINE

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BASED ON A SITEX NEGATIVE ION SOURCE^a

W. K. Dagenhart, W. L. Gardner, W. L. Stirling, and J. H. Whealton
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
(615) 574-1125

ABSTRACT

Scaling studies for a SITEX negative ion source to produce 200-keV, 10-A, long pulse D⁻ beams are under way at Oak Ridge National Laboratory (ORNL). Designs have been restricted to the use of established techniques and reasonably well-demonstrated scaling. The results show that the 1-A SITEX source can be directly scaled to produce 200-keV, 10-A long pulse ion beams with a source power efficiency of ≤ 5 kW of total plasma generator power per ampere of D⁻ beam generated. Extracted electron-to-D⁻ ratios should be ≤ 0.06 , with all extracted electrons recovered at $\leq 10\%$ of the first gap potential energy difference. The close-coupled accelerating structure will be 5 cm long and have five electrodes with 21 slits each, with a 50-kV/cm field in each gap. No decel electrode was included because of the transverse magnetic field. Electrons formed in each gap by the $\sim 16\%$ charge-exchange loss of D⁻ in the total accelerator column will be collected by electron recovery structures associated with the gaps at an average energy of 50% of a gap's potential energy difference. Atomic gas efficiency will be $\geq 67\%$. Beam divergence calculations using the ORNL optics code give $\theta_{rms} = \pm 0.4^\circ$. The ion source magnetic field provides momentum dispersion of the extracted beam, separating out both the electrons and all heavy ion impurities and low energy D⁰ particles formed by charge exchange in the accelerating column. A D₂ gas neutralization cell and a charge separation magnet provide 1 MW of D⁰ beam at 200 keV for injection. The overall beam line dimensions are $2.2 \times 1.0 \times 5.0$ m (H $\times$ W $\times$ L).

I. INTRODUCTION

Projected energy requirements for high power neutral beams on magnetic fusion reactors span the range from 150 keV on tokamaks using special programmed startup scenarios to 2 MeV

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for current-drive applications on tokamaks. All neutral beam heating projects to date on magnetic fusion experiments have used positive ion beam technology with gas cell neutralizers to form the neutral beam. The equilibrium neutral fraction emerging from such a gas cell is only 34% for a 150-keV D⁺ beam, falling to only 13% for 200-keV D⁺.¹ Clearly, above ~ 150 keV other means of beam generation must be used to maintain reasonable system efficiency. In addition, beams should be monoenergetic and free from heavy mass contaminants, and they should have a narrow angular divergence to minimize the size of the entrance port on the device. Current beam angle requirements range from $\leq 0.3^\circ$ on the Mirror Fusion Test Facility Upgrade (MFTF-B) to $\leq 1^\circ$ on tokamaks.

This study focuses on an intermediate energy requirement of 200 keV, well below the 600-keV dc acceleration of a 350-mA H₂⁺ beam accomplished on the ORNL DCX-II experiment.² With direct area scaling, a ≥ 10 -A accelerated D⁻ beam can be produced by a Surface Ionization Transverse Extraction (SITEX) source with an extraction grid area of 13×18 cm, about half the size of our present 50-A/80-keV rectangular D⁺ source. These results can be extrapolated from our present database, which includes results of 0.55 A at 18 keV and 10 s with the SITEX 1-A source module using single-gap extraction. To accomplish the D⁻ current goal with $\pm 0.4^\circ$ optics we assume a modest $\frac{1}{2}$ increase from the present best results of 62 mA/cm² for H⁻ up to 100 mA/cm² for D⁻ at the converter surface. Since the source is running at modest power densities, we assume that long pulse, dc operation will be possible when enough cooling is added.

For the gas cell, bending magnet, ion dump, and cryopump, we use ORNL designs that have been proven on both Princeton Large Torus (PLT) and Poloidal Divertor Experiment (PDX) positive-ion-based beam lines at Princeton Plasma Physics Laboratory (PPPL). The result is a 1-MW, 200-keV beam line, nominally the same size as the positive-ion-based PDX beam lines at 2.0 MW and 50 keV for D⁰. A larger ion source or multiple sources could be used to increase beam line output power without a proportionate increase in beam line

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size. This beam line can also be modified to use the more efficient plasma neutralizer or laser photoneutralizer once they are proven. Finally, this design has not been optimized for any particular application.

II. SITEX SOURCE SCALING RESULTS

The plasma generator, converter geometry, extraction system, electron recovery system, test facility, and 0.4-cm² extraction slit results have been reported for a flat, uncooled converter.^{1,3} Measurements have been made and reported for three extraction slits with areas of 0.4, 2, and 5 cm² for circular cylindrically curved molybdenum surface converter geometries.⁴ Figure 1 shows the latest geometry, which uses the gaseous helium cooled converter. Tests with the uncooled (600–800°C) geometries show extracted current scaling directly with extraction area. Table 1 summarizes the results. A recent test of the geometry shown in Fig. 1 but with gaseous helium cooling resulted in a dramatic increase in current and pulse length to 0.65 A for 9 s at 18 keV.⁵ Results are summarized in column 1 of Table 2. Power supply limitations prevented attaining an even higher current.

Table 1 shows electron extraction current ratios $I_e/I_{H^-} \sim 3-5$, which have been measured for both the flat converter^{1,3} and the curved converter geometries.^{3,4} The primary positive ion discharge column edge was about 0.8 mm from the back edge of the plasma grid extraction

Fig. 1. Side view of the ORNL SITEX plasma generator with a GHe cooled converter designed for 1 A of extracted D⁺ ions, used with the four-slit, 5-cm² extraction experiment.

Table 1. Performance of the SITEX plasma generator short and long slit extraction system using H⁺ to H⁻ converter cylindrical focusing and no converter cooling

	Short slit ^a system	Single long ^a slit system	Multiple long slit system ^a
I_{H^-} (analyzed/extracted) (mA)	~20/25	~60/75	>50/250 ^b
j_{H^-} (analyzed/extracted) (mA/cm ²)	~50/63	~30/38	>10/50
Beam energy (keV)	~23	~22	10–20
Atomic gas efficiency (%)	~2	~2	3
Converter geometry	Cylindrical focused	Cylindrical focused	Cylindrical focused
Beam divergence, θ (HWHM)	$\sim 2 \pm 1^\circ$	$\sim 2 \pm 1^\circ$	$\leq 2 \pm 1^\circ$
Extraction slit size (cm)	0.16 × 2.54 (0.4 cm ²)	0.16 × 12.7 (2 cm ²)	Four 0.24 × 5.2 (5 cm ²)
I_e (extracted)/ I_{H^-}	~3	~3	0.2
I_e (at V_{accel})/ I_{H^-} (%)	<1	<1	<1
I_e (at 10% V_{accel})/ I_{H^-} (%)	>99	>99	>99
(Source power)/ I_{H^-} (kW/A)	~190	~50	13
Plasma generator reliability (%)	~100	~100	~100
Converter temperature (°C)	600–800	600–800	600–800
Converter temperature control	None	None	None
Pulse length (s)	3	2	5

^aFirst experiment.

^bHigh pressure over a 23-cm path length and 90° magnetic deflection causes losses, which approximately agree with charge-exchange calculations.

Table 2. Present and 1-MW beam line scaled, ORNL SITEX negative ion source performance

Parameters	Achieved performance ^a	Scaled performance
Beam voltage (kV)	18.0	200
Beam current (A)	0.625	13
Pulse length (s)	9	dc
Energy/pulse (kJ)	101	
Duty factor	0.1	1.0
Averaged (dc) beam power (kW)	1.1	2000
j_{H^-} , extracted current density (mA/cm ²)		
	125	200
Extraction area (cm ²)	5	65
Normalized emittance ($\pi \cdot \text{cm} \cdot \text{mrad}$)		0.003 ^b
Beam divergence ($^{\circ}\text{rms}$)	± 2.7	$\pm 0.4^b$
Gas flow (torr-liter/s)	1.90	1.80
Source pressure (mtorr)	4 ^c	2
Source power/A H^- (kW/A)	5	3
Extracted electron to ion ratio	≤ 0.2	< 0.06
Extracted electron recovery efficiency (%)	> 99	> 99
Grid loading (% of $I_{H^-} \times V_{\text{accel}}$)	≤ 10	2
j_{H^-} , grid-averaged extracted current density (mA/cm ²)	28	56
Accelerator electron recovery (%)		100
Accelerator electron loading (% IV)	0	< 3
Impurities in neutral beam (%)	$\leq 0.001^d$	< 0.001
Neutral beam energy spread (keV)	$0.95 \leq E_b \leq E$	$0.95 \leq E_b \leq E$

^a1-A SITEX source, pulsed mode, simultaneous values.

^bCalculated from ORNL 2-D optics code.

^cAssumes a gas temperature of $\sim 500^{\circ}\text{C}$.

^dSource impurities of 1% are analyzed out by the source magnet.

slit. For the 5-cm² test, that distance was increased to 3.8 mm by curving the discharge column as shown in Fig. 1. This resulted in a much lower I_e/I_{H^-} ratio of ~ 0.2 ; this result agrees with previous Cl^- beam extraction results under similar conditions.⁵ Observation of the source during long pulse operation confirms the electrical measurements, which show that almost all of the extracted electrons are collected at energies of $\leq 0.1 V_{\text{accel}}$. Note that this is a test of the electron recovery system^{1,3} under multislit conditions.⁴

Long pulse operation was limited to 10 s since most plasma generator parts were not cooled; the extractor slit insert was uncooled but was fastened to a water-cooled stainless steel holder. Long pulse, dc operation will probably require cooled accelerator grid structures.

Table 1 shows that the I_e/I_{H^-} ratio has been lowered by a factor of ~ 15 and that the power efficiency of the source has been increased by a factor of ~ 15 using the column 3 geometry. Columns 1 and 2 of Table 1 are results from the single-slit first experiments that were obtained at a reasonable tank pressure of $\leq 2 \times 10^{-4}$ torr and correspond to a charge-exchange loss of $\sim 20\%$ from the extraction slit to Faraday cup. Results from the first test of the 5-cm² extraction geometry, presented in column 3 of Table 1, were obtained at very high pressures due to limited pumping speeds. A pressure increase of about 7 would be required to increase the charge-exchange loss from 20 to 80% if the gas were H_2 . The actual operating pressure was ~ 5 times higher as measured on a Bayard Alpert gage. We attribute the loss represented by the ratio of 250 mA extracted to 50 mA analyzed to charge exchange. Approximately

99% of the extracted electron current ($\sim 20\%$ of I_{accel}) does not circulate through the accel supply, but only through the electron recovery supply at an energy loss of $\sim 2-3$ keV. We have thus equated I_{accel} to I_H^- since the source had been well outgassed and impurities were estimated to be $\sim 1\%$ of I_{accel} .

Column 1 of Table 2 gives the most recent SITEX source performance with the converter temperature controlled by gaseous helium flow. Both beam current (and extracted current density) and pulse length have been doubled. Longer pulse/dc operation will be possible with a newly designed converter that will shield the cold gaseous helium cooled areas, which now pump cesium from the discharge.

III. 200-keV, 10-A, LONG PULSE SITEX SOURCE CONCEPTUAL DESIGN

In the conceptual design we assume that I_D^- can be scaled from the results shown in Table 2. A single, large, cooled converter with the geometry shown in Fig. 1 behind each slit was used. The hot filament, hollow cathode type of electron feed was also used. An extraction slit 0.24×13 cm with a 6.4-mm-wide fluid-cooled slit was selected, resulting in a geometrical transparency of 27%. We make a modest extrapolation to $j_D^- = 100$ mA/cm² at the converter and a converter surface with cylindrical focusing. By using a 21-slit, 13×18 -cm extraction area, we obtain $I_D^- = 13$ A of extracted current. Figure 2 shows the plasma generator with the accelerator structure.

The operating pressure is a fundamental property of the discharge and is now about 2 mtorr. For 2-mtorr anode pressure and the calculated gas conductance of the 5-grid system, the source atomic gas efficiency would be $\sim 67\%$. The expected value of I_e/I_D^- is 0.06, as calculated from the $I_e/I_H^- = 0.2$ value in Table 1 and the $1/B^2$ dependence of I_e at the higher B necessary because of D^- operation at 200 keV. This value of I_e can be handled with the present recovery system design, which has been tested up to $I_e = 1$ A. The recent ion source performance⁵ has resulted in a considerable improvement in scaled source⁷ and beam line performance⁸ over that previously reported.

Making only modest extrapolations from the present database, we have shown that the SITEX source can be configured to generate a 200-keV,

Fig. 2. A 200-keV 10-A, long pulse SITEX source and accelerator.

10-A, long pulse D^- beam. Aggressive source development could more than double the beam current to >20 A by electron feed development. By three-dimensional contouring of the converter surface, adjustment of its voltage, and accelerator design we expect to lower beam divergence below the $\theta_{\text{rms}} = \pm 0.4^\circ$ presently calculated.^{8,9}

Figure 3 shows the angular divergence pattern calculated for the SITEX source for one geometry at a first grid extracted current density of 200 mA/cm².

Fig. 3. Accelerator design for the 200-keV/10-A D^- beam line.

IV. BEAM LINE CONCEPTUAL DESIGN

Our philosophy for this system was to create a design based upon the present database and proven technology and to develop it in sufficient detail for credibility. This philosophy was chosen to provide a basis for the earliest possible demonstration of 200-keV negative ion technology.

In examining the subsystems within a negative-ion-based neutral beam system, it can be seen that the system is similar to a positive-

ion-based system. Inherent differences lie (1) in the negative ion generator and in how it couples to the accelerator, (2) in the need for an electron removal scheme in negative ion systems, and (3) in the physical properties of the neutralizer. The parameters of each subsystem are not independent of each other or of the parameters of other subsystems.

As a first step we determined that the most important parameters were the ion source current density, beam divergence, and ion source pressure. Practical limits for these parameters are a current density at the extraction slit between 100 and 300 mA/cm², a beam divergence of <1°, and a source pressure between 1 and 3 mtorr. The lower limit on current density reflects the fact that densities below this level need an overlarge beam system to produce the 10-A extracted current required. The upper limit was set to keep the beam divergence to <1° (due to space charge broadening). The beam divergence limit is the result of positive ion beam line experience and was set to minimize beam line size. The lower limit on source pressure was necessitated by the arc discharge requirements in the SITEX source negative ion generator. The upper limit was based upon the highest acceptable D⁻ beam stripping loss in the accelerator structure.

The following assumptions were made from the database in column 1 of Table 2. We have chosen 200 mA/cm² (100 mA/cm² at the converter) for this design. Theoretical modeling^{8,9} gives divergences of ±0.4°. A source pressure of 2 mtorr is based upon the measured throughput and calculated conductance for our present negative ion source. The negative ion source considered for this design is a scaled version of the 1-A SITEX plasma generator and extraction system. Figure 2 is a 200-keV, 10-A, steady-state SITEX negative ion source. To scale up to this 10-A source module we used the present SITEX slit dimensions of 13 × 0.24 cm and an accelerator stripping loss of 20% based on calculations discussed later. Producing 10 A of negative ion current at 200 keV requires 13 A of negative ions at the accelerator entrance. This implies 21 slits based on current density and slit size. The interslit spacing is 6.2 mm to leave room for cooling channels, so total extraction dimensions are 13 × 18 cm. The accelerator was scaled to accommodate the 200-keV beam energy requirement. Direct electrostatic acceleration was assumed. The electrodes will be kept hot to minimize cesium condensation and resulting arcing and adopt a conservative field strength of 50 kV/cm for each gap. The gap spacings were limited to 1.0 cm each and the grid thickness was 2.0 mm, resulting in a five-grid structure

with a 5.0-cm overall length. A cursory examination indicated that a decel or suppressor grid would be unnecessary.

In sizing a negative ion source and estimating system losses we must estimate the amount of premature stripping of negative ions that will occur in the accelerator. For the slit size and accelerator length used, a conductance of ≈15 l/s/slit was calculated. Based on a 2-mtorr source pressure, the throughput per slit is ≈3 × 10⁻² torr·l/s. The stripping cross section is a function of particle energy and thus of distance through the accelerator. Combining this with the changing gas density across the gap and integrating yields an estimated total stripping loss of (16 ± 5)%. The upper bound of the uncertainty was used to size the source.

Source gas efficiency can be directly calculated from the given data. The throughput equivalent of 13 A is $Q_b = 1.2 \text{ torr}\cdot\text{l/s}$, and the source gas throughput is 0.6 torr·l/s. Hence, the source gas efficiency is $\eta = Q_b / (Q_b + Q_s) = 0.67$.

With the ion source specified, the other components can be sized. Because the accelerator must be operated with minimum pressure in the gaps, the neutralizer must be uncoupled. A conventional gas stripping cell was chosen and assumed to be center fed to minimize throughput and length. The line density for maximum stripping at 200 keV is $4 \times 10^{15} \text{ cm}^{-2}$. The neutralizer cross section was set at 17 × 22 cm as a compromise between minimizing power loading due to beam divergence and minimizing gas conductance. A 2.0-m cell length provided the best compromise between the gas cell length and gas throughput to achieve the needed line density. Four cryocondensation cryopanel of the PLT/PDX design were used to provide 500 kl/s of effective pumping speed.

At this energy, the ion fraction remaining at the stripping cell exit is approximately half positive and half negative ions. Hence, two ion dumps are needed, each able to handle approximately 0.4 MW. Conventional technology should be adequate. Figure 4 shows the beam line system. The source magnetic field combines with the accelerating field to form an $\vec{E} \times \vec{B}$ electron recovery system. The momentum dispersion of the magnet separates the low energy D⁻ ions and heavy impurities from the main D⁻ beam. The low energy charge-exchange D⁰ particles (≈16% of the extracted beam) do not receive full magnet deflection and are not transmitted. A 40% ion fraction remains at the neutralizer exit (approximately equal D⁺ and D⁻ fractions) and is separated from

Fig. 4. The momentum separation function of the SITEX source magnetic field.

the beam by a bending magnet. The remaining beam has no high energy electrons, $<10^{-5}$ impurity fraction, beam energy E_b of $0.95 < E_b < E$, and $\theta_{rms} = \pm 0.4^\circ$. The calculated scaled performance of the 200-keV/1-MW D^0 beam line is given in column 2 of Table 2.

Figure 5 shows the overall beam line, which is $2.2 \times 1.0 \times 5.0$ m (H $\times$ W $\times$ L), nominally the same as the positive-ion-based systems on PDX with about half the neutral power of the PDX system but approximately four times the injected particle energy and no fractional energy or

Fig. 5. A 1-MW/200-keV beam line design based on the ORNL SITEX negative ion source.

impurity components. We conclude that with proven technology and a small extrapolation from our present database, we can achieve a compact, efficient, high energy, negative-ion-based neutral beam system.

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