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ACCELERATED BEAM EXPERIMENTS WITH THE ORNL SITEX AND VITEX H^-/D^- SOURCES*

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ABSTRACT

Beam parameters have been measured for both the Surface Ionization with Transverse Extraction (SITEX) and Volume Ionization with Transverse Extraction (VITEX) H^-/D^- ion sources. Both sources use a reflex discharge to generate the main plasma. Beam energies up to 18 keV were used for pulse lengths up to several seconds. For SITEX, Faraday cup magnetically analyzed D^- beam currents of 110 mA at extraction densities of 48 mA/cm^2 and at a source ion temperature of 4 eV have been measured. For the VITEX results, Faraday cup magnetically analyzed beam currents of up to 80 mA at extraction densities of 27 mA/cm^2 and at a source ion temperature of 0.5 eV have been measured. Virtually all extracted electrons were recovered at an energy of 10–30% of the accel beam energy, and there were none in the analyzed beam.

INTRODUCTION

The original SITEX and VITEX H^-/D^- ion sources were configured for fusion applications to provide eventual scaling to >10-A beams at energies above 200 keV for multisecond pulse lengths.[1–9] This hardware and these concepts are now being adapted to produce high-brightness, negative-ion beams for radio-frequency quadrupole (RFQ) acceleration. The goal here is to produce much smaller beams at 100 keV for further RFQ acceleration and for pulse lengths ranging from the submillisecond level through many seconds to steady state. The present sources are at the proof-of-principle stage and are evolving rapidly. The SITEX results presented here are from December 1985 to May 1986, after which the effort concentrated solely on the VITEX source. Since that time the hardware and results have been evolving rapidly. The VITEX results included in this paper are from May 1986 to October 1986.

The main goals of the SITEX experiments reported in this paper were (1) to use an emittance scanner on the accelerated beam to determine the source plasma generator ion temperature and (2) to determine the beam emittance. The VITEX experiments were aimed at developing higher beam current and beam current density and measuring the source ion temperature with an emittance scanner. Secondary goals of both sets of experiments were the development

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of plasma generators[10] and accelerators that would operate for short pulses, for long pulses, and steady state. Other goals were to improve gas efficiency, beam brightness, and arc efficiency; to reduce beam emittance and extracted electron current; to provide low-energy collection of electrons that are extracted; and to develop reliable systems with faster startup and with good endurance.

EXPERIMENTAL APPARATUS

Both VITEX and SITEX used a reflex discharge with a hot cathode electron emitter on one end of the discharge and a biased electron reflector on the other end. A second version of these sources replaced the reflector with a hot cathode electron emitter that essentially doubled the amount of arc power that could be put into the arc plasma. A biased electrode was mounted behind the discharge, as shown in Fig. 1.

Gas was independently fed to both cathode cavities and the anode cavity. Figure 1 shows the hookup of the independently controlled two-filament, two-arc discharge and one converter supply. The figure also shows that single gap extraction was used. For SITEX, cesium was fed from a temperature-controlled oven; secondary control was provided by a manually adjusted high-temperature series valve. The ion source was operated in an adjustable uniform magnetic field. Vacuum was provided by two oil diffusion pumps with a delivered speed

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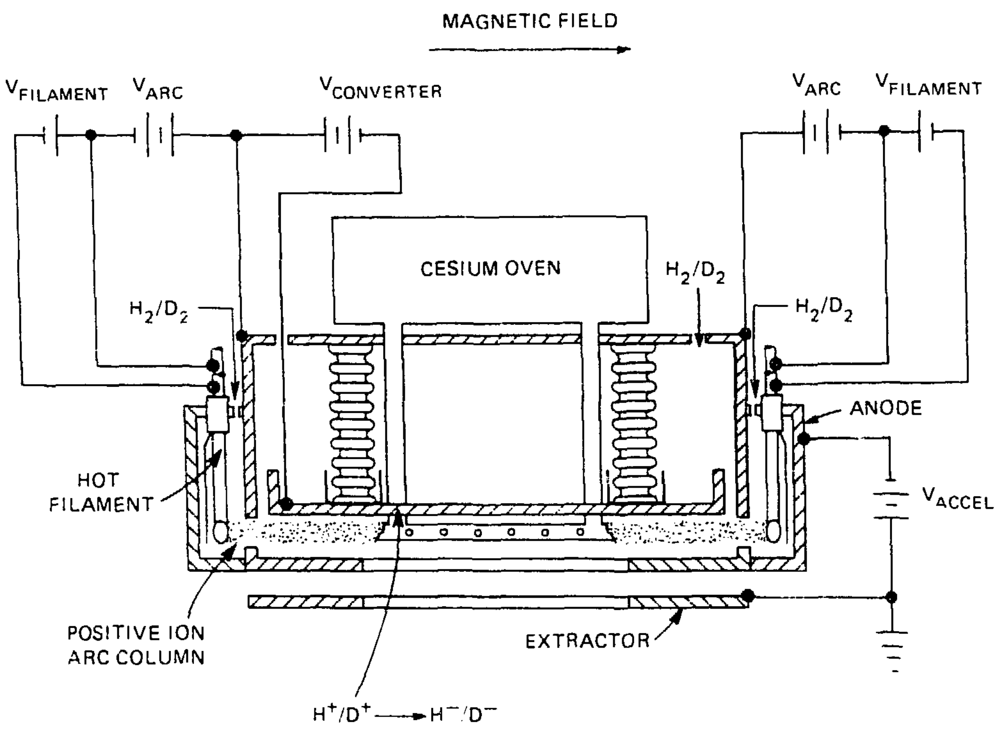

Fig. 1. Top view of plasma ion source, showing power supply connections.

of ~2000 L/s at the source. Faraday cups and electron recovery electrodes were operated in the magnetic field with secondary electron shields to provide complete current accountability. Two LANL-type emittance scanners[11] were used to measure the x- and y-plane emittances transverse to the beam propagation direction. Figure 2 shows the source and the diagnostic structure. The arc chamber was machined from graphite and was then plasma sprayed with molybdenum. The arc collimating slot was also machined from graphite and plasma sprayed. For SITEX operation, the graphite structure ran at high temperatures, controlled so as to control the location of cesium in the arc chamber. Plasma grids were machined from molybdenum.

Electrons extracted with the H^-/D^- beam were separated from it immediately after extraction by the $\mathbf{E} \times \mathbf{B}$ forces and cycloided up the front of the

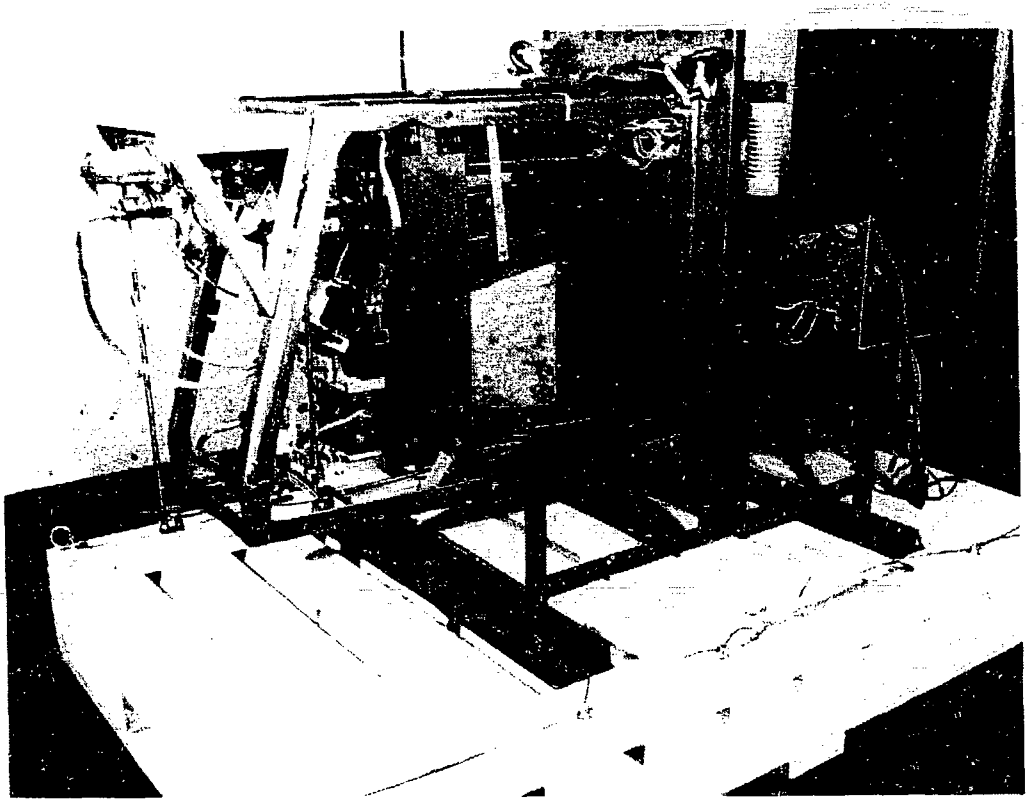

Fig. 2. SITEX/VITEX ion source assembly with diagnostics attached.

plasma electrode to a recovery electrode biased positively with respect to the plasma generator. The recovery voltage needed to collect virtually all electrons varied between 10% and 30% of the first gap potential difference. Electrodes were used to measure the small number of electrons that were not recovered, and these proved to be negligible. All of the SITEX and some of the earlier VITEX experiments used an optics system that was optimized for beam focusing only in the direction perpendicular to the long slit. Since the magnetic field was uniform and in the direction of the slit, we could also measure beam profiles in the direction of the slit without the effects of ion optics and could then calculate the ion temperature of the extracted ions. Most VITEX measurements used extraction slits for which the optics have not been calculated. Both the extraction gap and the electrode relative locations could be adjusted during all experiments. The emittance scanners were mounted to scan in two orthogonal directions, which were also orthogonal to the beam path after it had been deflected through 90° in the uniform magnetic field. All beam currents were obtained by measuring the current voltage drop across small resistors with oscilloscopes or with the computer system analog-to-digital converters. All of the emittance data presented were measured over a 30-ms period during the multisecond beam pulses. One emittance scan of beam angle versus beam current was taken for each of 15 to 30 mechanical slit positions as it scanned across the beam. Each mechanical position required one multisecond beam shot with data taken for 30 ms at the same point in time during each pulse.

SITEX AND VITEX EXPERIMENTAL RESULTS

Table I lists the SITEX parameters achieved with cesium operation during the production of D^- beams. Generally, pulses lasting 3 to 10 s were run every 60 s. The repetition rate was mostly determined by our data acquisition system, and in order to eliminate repetition rate as a variable it was held constant during these experiments. Some modes of operation gave flat beam current pulses after about 1 s both for VITEX and SITEX. Square short pulses with a sharp rise time generally had to be achieved with source parameters different from those required for long, flat pulses. Figure 3 shows a set of SITEX beam waveforms in which the beam pulse came to equilibrium in about 0.25 s. Figure 3(a) shows an acceleration voltage of ≈11 kV and an acceleration power supply drain current of 175 mA. The Faraday cup was located about 3 cm from the extraction grid in a uniform magnetic field and measured 100 mA of H^- current. Beam interception by the extractor grid was ≈70 mA, leaving about 5 mA for unrecovered electrons that received full energy. These electrons were magnetically removed from the beam. Figure 3(b) shows the electron recovery current of ≈100 mA at a recovery energy of ≈4 keV. A shaped focused converter as specified from the ORNL optics code was used and had a current of ≈8 A and voltage of −130 V with respect to the anode. Notice that the electron recovery current doubled for about 100 ms when the arc and converter were pulsed off. Figure 3(c) shows a fairly constant arc pulse at 90 V and 6 A. The highest parameters have so far not been achieved with flat beam pulses but show a single maximum somewhere during the pulse.

Figure 4 shows a similar set of beam traces for VITEX with an H^- beam. Here the system reached steady state after 1.5 s. Note that the reflector (reflex

Table I. Source experimental status

Parameters (simultaneous)	VITEX status (H^-) Long Pulse	High current density	High current	SITEX status (D^-)
H^-/D^- current, mA	19	25	80	110
H^-/D^- extraction current density, mA/cm^2	6.3	125	27	48
Pulse length, s	5.5	0.500	0.100	10
Voltage, kV	16	15.8	16.4	10
Brightness, mA/cm^2·eV	13	310	67.5	12
Source pressure, mTorr	9	192	—	10
Gas efficiency (atom^{-1}/atom)%	0.09	0.10	—	2
Electron control, % × IV	857	219	232	20
Arc efficiency (arc power/H^- current), kW/A	140	286	41	10
Reliability				
Turn-on, %	100	100	100	100
Full pulse, %	>95	>95	>95	>90
Electrode power loading, W/cm^2	<2500	<2500	<2500	<2500

discharge electrode opposite the hot emitter) voltage [Fig. 4(c)] is about −170 V with respect to the anode. The ratio of electron recovery current to beam current is much higher for VITEX than for SITEX. The current accountability,

$$I_{\text{drain}} = I_{\text{Faraday cup}} + I_{\text{extractor}} + I_{\text{electrons to ground}} \;,$$

gives about 13 mA of unrecovered electron current (electrons to ground) out of 1213 mA of electrons extracted with the H^- beam. This H^- current resulted mainly from the use of a high anode gas flow with no cathode or reflector gas and was restricted by the low (2000-L/s) pumping speed of the test facility, which resulted in pressures of $\approx 10^{-3}$ Torr and hence much charge-exchange loss of the beam. Figure 5 shows an intermediate beam current achieved by pulsing the gas but limited by pumping. The Faraday cup signal was actually $\approx$38 mA when corrected for beam that passed through a small hole in the Faraday cup. Electrons accelerated to ground are the sum of the side shield current and the top plate current. The 1/8 SLP (μA) is the current that passed through the

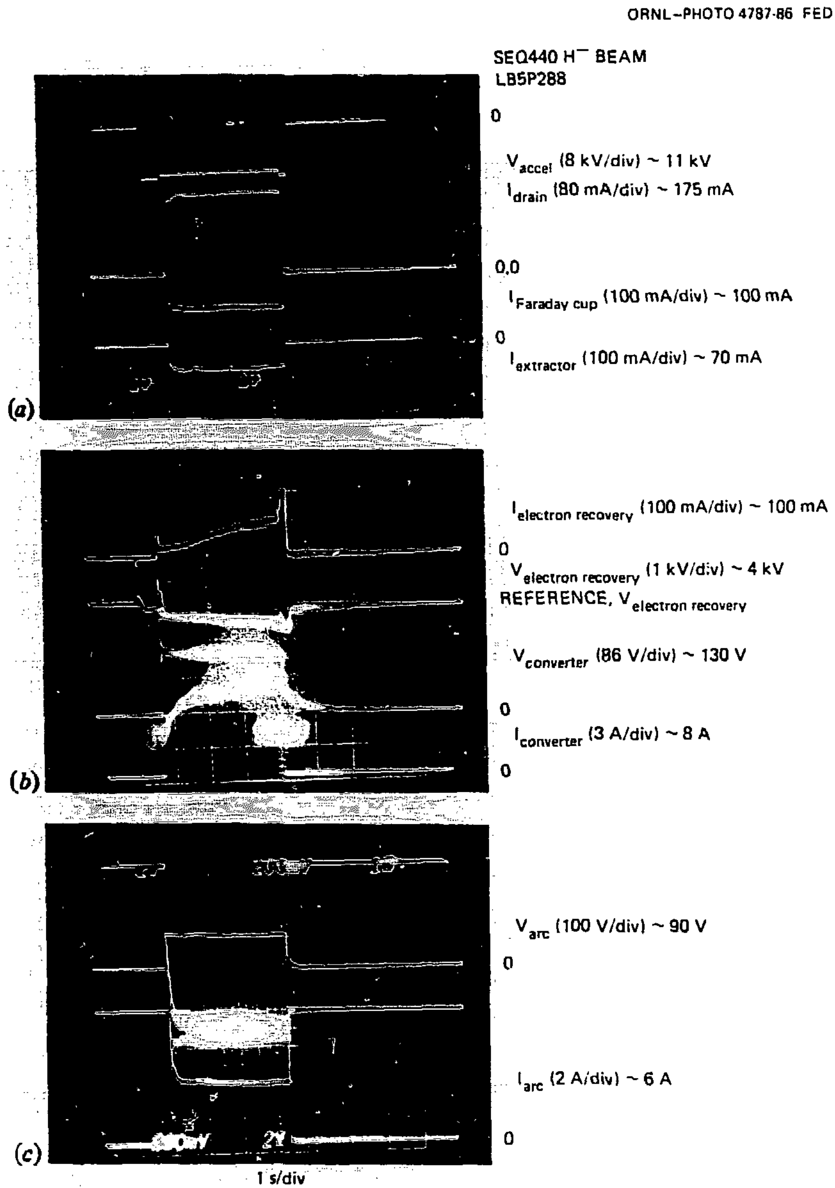

Fig. 3. SITEX beam waveforms with the source adjusted for a flat pulse.

Faraday cup and was not charge exchanged in the 23-cm flight path to the emittance scanner.

In Table I the high electrode power loading was on the graphite arc collimating slot. An intermediate arc electrode has been successfully tested and removed most of this power from the collimating slot, but it was not used for any of the data reported in this paper. It will be used when conversion to an all-metal VITEX source occurs.

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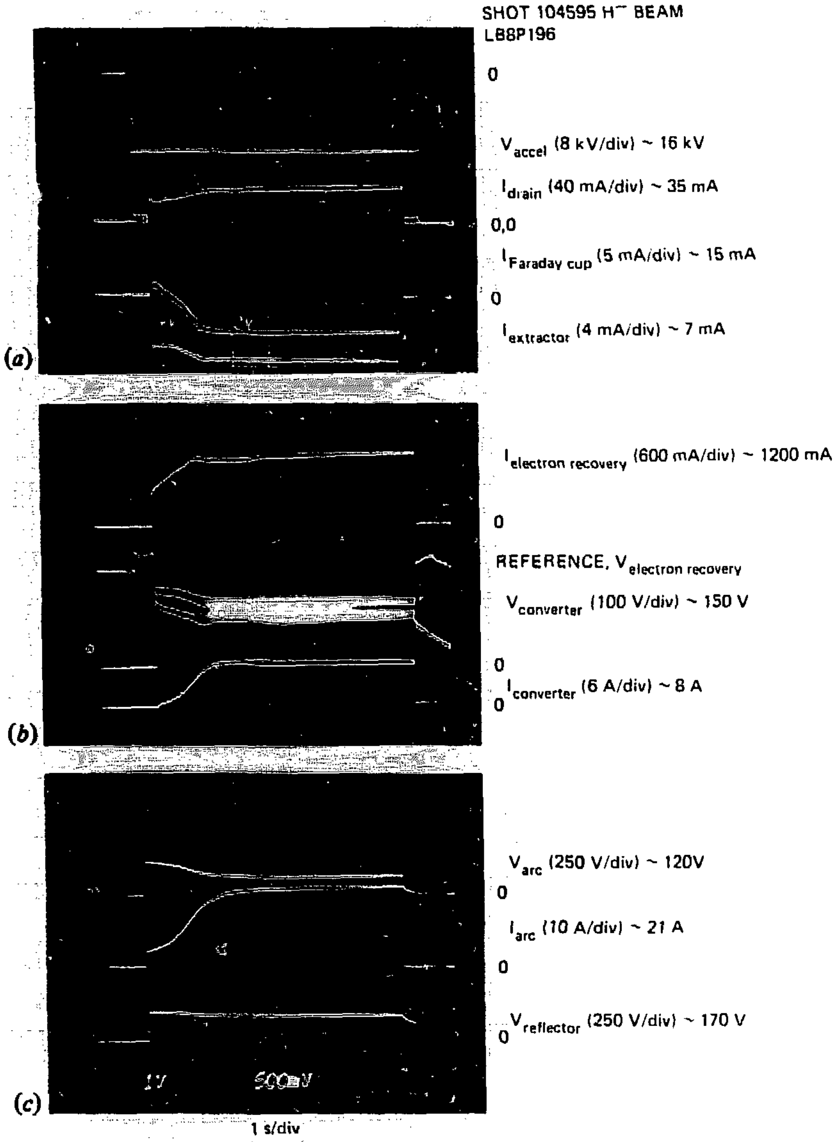

Fig. 4. VITEX beam waveforms with the source adjusted for a flat pulse.

ION TEMPERATURE AND EMITTANCE DATA

Figure 6 shows the layout of the emittance scanners, which are of the LANL type employing parallel plate electrostatic scanning. The emittance measurement is performed after 90° of beam deflection in a homogeneous magnetic field. Emittance measurements are made both parallel and perpendicular to the magnetic field. Figure 7 shows the beam current density distribution from an emittance scan parallel to the magnetic field.

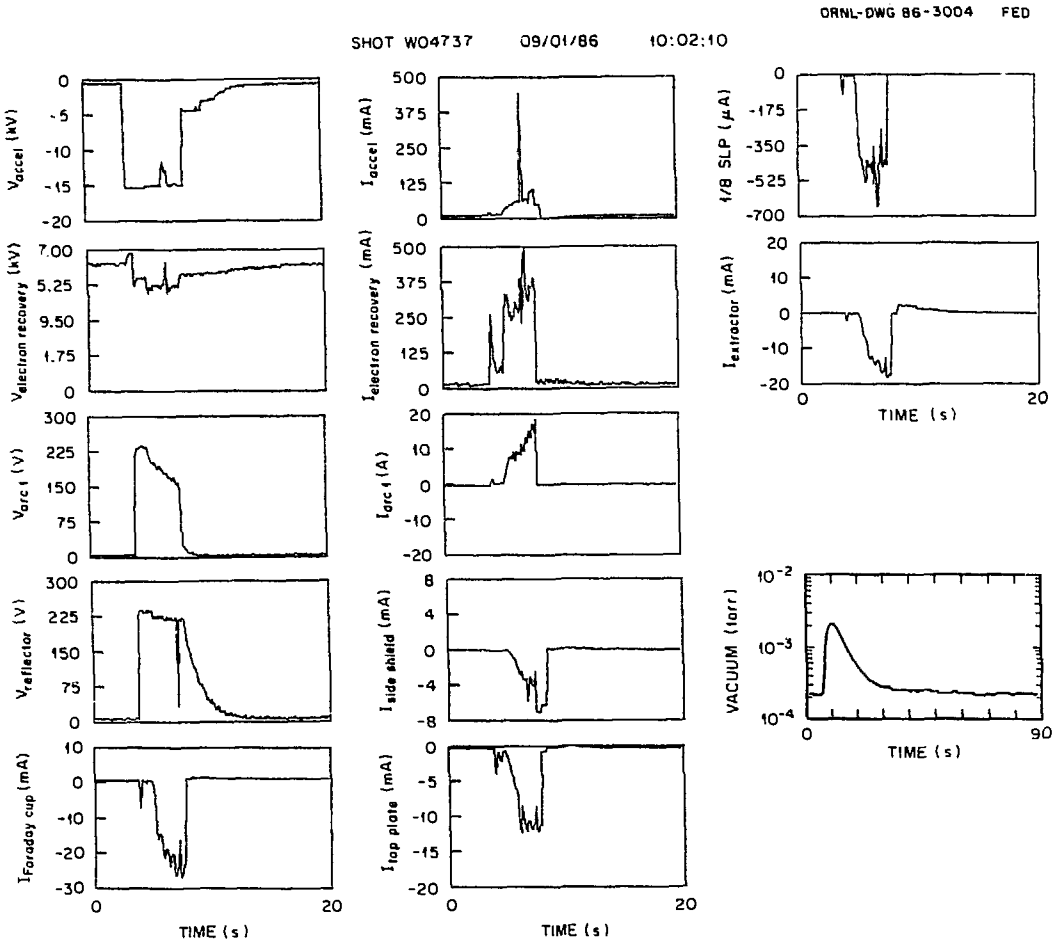

Fig. 5. VITEX beam waveforms using pulsed gas.

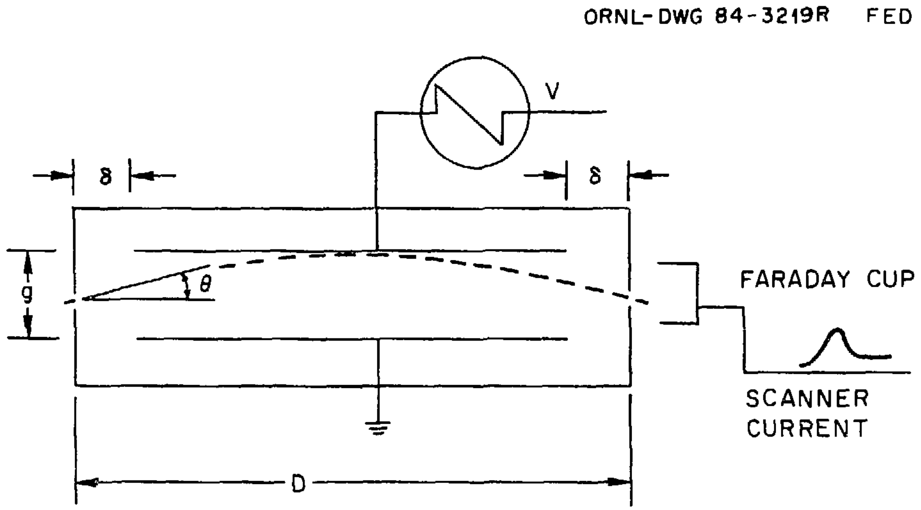

Fig. 6. Emittance scanner layout using parallel plate deflection.

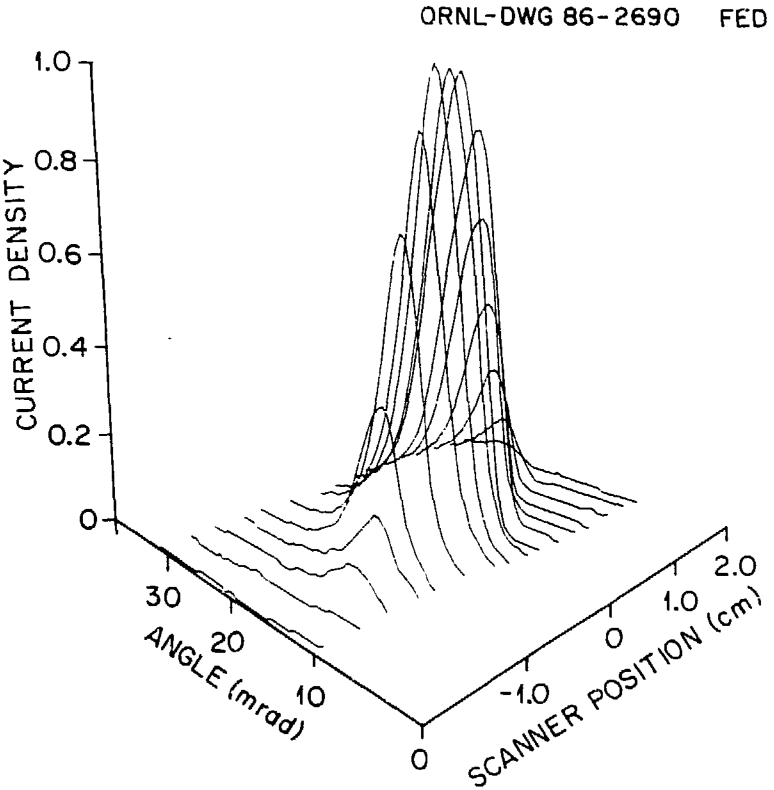

Fig. 7. Beam current density after 90° of beam deflection, derived from an emittance scan parallel to the magnetic field.

The orthogonal coordinates x,y,z are used to describe the beam at the emittance scanner, where y is parallel to the magnetic field B, x is perpendicular to B, and z is the direction of beam propagation. An emittance scan parallel to the magnetic field is done using a slit that is long enough in the x direction to integrate over $I(x,x')$. The slit is moved incrementally over the full extent of the beam in y so that the distribution $I(y,y')$ is measured. The source ion exit slit is long in the y direction. By measuring the center of the beam for $I(y,y')$, one can calculate the source ion temperature, since neither the source accelerator nor the magnetic field affects $I(y,y')$. The same technique is used for the emittance perpendicular to B. For perpendicular scans the accelerator focusing affects the emittance. For an emittance scan parallel to B, assuming a Gaussian velocity distribution and using the $1/e$ point of the distribution, one gets

$$kT = eV\phi_e^2$$

where

kT - ion temperature

e = electronic charge

V = beam acceleration voltage

ϕ_e = angular width of the beam at the $1/e$ point.

Table II gives a summary of the ion temperature and emittance data for SITEX and VITEX. Ion temperatures are computed from the emittance measurements parallel to the magnetic field using the width of the angular distribution. Ion temperatures for VITEX at 0.5 eV are about a factor of 10 lower than those for SITEX. These ion temperature measurements using an emittance scanner are in reasonable agreement with those from other surface and volume ion sources.

SUMMARY

Ion temperatures in the source have been established at 0.5 eV for VITEX and at 4 eV for SITEX by use of an emittance scanner on the analyzed beam. Further improvements in the extracted current density for SITEX are expected with the increased arc power that will be available through the use of a triode arc discharge. Better control of the arc discharge is expected to result in faster turn-on and constant discharge characteristics.

The output H^- current and current density for VITEX have risen steadily in experiments during the last few months, which represent most of the work with this type of source. Future improvements in output current and current density are expected through use of the triode arc to permit higher arc power, geometry optimization, and biased plasma grid.

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Table II. Summary of typical ion temperature and emittance data

	SITEX		VITEX	
	Perpendicular measurement[a]	Parallel measurement[b]	Perpendicular measurement[a]	Parallel measurement[a]
Source slit dimensions $x \times y$, cm^2	0.21 × 0.16	0.21 × 0.16	0.1 × 2.0	0.1 × 2.0
Normalized rms emittance, π·cm·mrad	0.010 ± 0.005	0.003 ± 0.001	0.013	0.017
Normalized emittance (63% beam fraction)	0.010 ± 0.005	0.005 ± 0.002	—	—
Ion temperature at extraction, eV	6 ± 2	4 ± 2	—	0.5 ± 0.1
Current density j_{H^-}, mA/cm^2	48	48	60	60
Beam current I_{H^-} included in emittance, mA	—	—	8.3	8.3

[a]Entire beam emittance in this direction.

[b]Partial beam emittance in this direction. Useful for determining ion temperature without effects of beam optics.

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