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A PULSED XENON MEGAWATT ARC PLASMA SOURCE

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ABSTRACT

The exhaust of the source flowing into vacuum was measured by Thomson scattering diagnosis. Mean electron temperatures and densities were found to be 4-8 eV and of order 10^{13} cm^{-3} respectively over the 8 cm exhaust diameter at 30 cm from the source. Large shot to shot variations were noted. After a transient spike passes, these conditions persist during the power time of 125 μsec. These exhaust conditions are marginal for evaluation of a proposed near resonant charge exchange pumped laser theory.

INTRODUCTION

The exhaust from a pulsed megawatt gas-fed arc plasma source may serve as a suitable medium for a type of laser suggested in a paper by Chubb and Rose.[1] The charge exchange laser proposed in that paper can best be examined experimentally if the plasma conditions for obtaining gain are independent from the source of ions. Suitable xenon exhaust conditions are 2 to 3 eV electron temperature and 10^{14} cm^{-3} number density. A pulsed gas-fed arc plasma source under investigation at Lewis Research Center and discussed in papers by Michels, et al.[2-4] could possibly provide these needed plasma conditions.

This paper describes the initial experimental investigation of the exhaust using xenon propellant as suggested by Chubb and Rose, reference 1. Earlier work[2-4] was done with different propellant, vacuum facility, power supply, and gas valve. The exhaust characteristics described in this paper are not only for a new propellant but also for improved facilities and system.

APPARATUS

Vacuum Facility

The initial experiments[2-4] employed a glass pipe exhaust flow duct, 15.2 cm i.d., 3 m long which was pumped by a 25.4 cm diameter diffusion pump system. The experiment was recently moved to a much larger vacuum facility. This facility is shown in figure 1. The vacuum tank is 5.3 m long by 1.55 m in diameter and is pumped by 4 diffusion pumps, each 0.9 m in diameter. The thruster is mounted on an insulating flange on an electrically floating insulated spoolpiece, 0.9 m in diameter by 0.9 m long. Both the old vacuum system and the new facility were pumped to the low 10^{-6} torr pressure range prior to each thruster pulse. The much greater throughput of the new vacumm facility allows millisecond thruster operation with large propellant flows (grams per second) without increasing the transient tank pressure above 10^{-3} torr. The larger diameter (1.55 m) of the new vacuum facility allows testing of the exhaust with much less wall interference.

Plasma Source

The source used in these experiments is the type described in references 2-4 for the self-field case. The arc chamber is shown in cross section view in figure 2. In figure 2(a) the puff propellant valve of references 2-4 is shown in place. Figure 2(b) shows the newly developed pulsed solenoid valve system that was used in this work. The anode for all the experiments was made of copper, 4.12 cm inside diameter. The cathode was a 1 cm wide, 1 mm thick, tungsten ribbon (2 cm long) and was not heated prior to each pulse. The arc chamber geometry was the same for all the experiments of this paper.

Propellant Systems

The experiments of references 2-4 employed an electromagnetic hammer actuated high-speed puff propellant valve system. This system was employed in the earilier phase of the plasma source program where the vacuum facility was small and had low throughput capability.

In the new vacuum facility the plasma source was operated with a newly developed pulsed solenoid valve propellant system. A commercially available miniature solenoid valve was modified to allow a maximum flow rate of 3.5 g/s Xe. The valve was fed from a regulated high pressure reservior. Instead of the usual 115 VAC, 60 Hertz, solenoid excitation, the solenoid was driven with a specially shaped voltage pulse. This pulse was generated by a gated reed relay system that applied a 350 volt spike, decaying in one millisecond to 100 Volts. The latter portion of this applied voltage lasts for 10 milliseconds. The valve is "full open" in 2 milliseconds and steady flow is established through the arc chamber in 3.5 milliseconds. At this time the arc is ignited. Although the arc is powered for only a few hundred microseconds, the exciting electrical pulse lasts for 10 milliseconds. Thereafter a spring internal to the valve closed the valve after 40 milliseconds.

Power Supplies

The experiments of references 2-4 were powered by a capacitor bank[5] that was crowbarred at peak current to provide a monotonically decaying arc current for a few hundred microseconds.

A different type of power supply was used to power the thruster for the work reported herein. This is a newly developed pulse-forming network (PFN) capacitor bank[6] that provides a square wave powering current for the arc. The PFN-capacitor bank provides up to 20 kiloamperes current for 125 microseconds and is shown with its solid state switching in figure 3.

Number Density and Electron Temperature Measurement

The electron number density and electron temperature of the exhaust were measured using 90° Thomson scattering of the beam from a Q-spoiled ruby laser light pulse as described in reference 3. For this experiment, the laser power was increased, using an auxiliary optical amplifier, and the scattered light optics were improved significantly to obtain almost an order of magnitude increase in sensitivity.

RESULTS AND DISCUSSION

The gas-fed plasma source was powered for 125 microseconds with a 16 kA square wave pulse. The exhaust characteristics were measured for four different propellant flow rates. After the propellant valve was opened, a time period of 3.5 milliseconds was allowed for stable flow through the source. Then the arc was powered.

Electron temperature and electron number density were determined by measuring the scattered light from the plasma illuminated by a pulsed laser. This requires many single shot operations of the plasma source. A corresponding number of laser pulses and scattered light measurements are made, each at a known time in the exhaust event. A set of ten source operations and corresponding measurements are made for each time of interest in the exhaust. This time is referenced to arc ignition time.

A typical set of data at the center of the exhaust (R = 0) at 30 cm downstream of the anode (Z = 30 cm) is shown in figure 4. The electron temperature is shown in figure 4(a). Each data point is the mean value of ten separate exhaust pulses. Data were detectable starting at 51 microseconds and were measured to shortly after 160 microseconds where they go below detectable limits. There is a shot to shot variation in the exhaust. This noted by the spread bars on the data points. The mean of the measured signals is used to calculate a mean electron temperature. The mean deviation of the measured signals for a fixed time in the event is used to calculate the deviation in electron temperature denoted by the spread bars. Once a mean electron temperature is measured, a mean electron number density can be determined from the intensity measurement of the scattered light (fig. 4(b)) at a single wavelength. The spreads in electron temperature and intensity determine the spread bars for electron number density.

The earliest plasma detected occurred at 51 microseconds in the 1.55 m exhaust duct. There is an initial transient spike of pressure at this time, noted earlier in reference 4. An initial high number density is measured at that time. It has not been determined if this is a true density or whether a part of the scattered light might be produced by turbulent transients. The mean densities thereafter (60-100 μsec) varied from 1.2 to 1.7×10^{13} cm^{-3} with corresponding electron temperatures ranging from 6-15 eV. The data spread bars in number density extend almost an order of magnitude at some times and only by factors of two at other times. This is not a limitation in the measuring system. It is the shot to shot variation in the exhaust: the calculated number density data spread is enhanced by the exponential sensitivity of number density to electron temperature.

The data were gathered in this fashion for four radial positions at $Z = 30$ cm and for four different mass flow rates of the source. Rather than log the measurements for each time increment of each survey, a mean electron temperature and a mean electron density were determined from plots similar to figure 4 for the time period (40-80 μsec) after the transient spike event. These mean values are shown in table I.

In the previous experiment (ref. 3) a reduced density ("hole") was noted on the axis of the exhaust. This was detected only for cases where the source used an auxiliary magnetic field. In the present data a slight reduction of number density is noted on the axis, even though no auxiliary field was used. The increased sensitivity of the present measuring system makes this detectable. The effects of annular mass injection and the self-magnetic field of the source (which impede ion drift to the centerline) combine to reduce the number density on the axis.

There appears to be a small effect of mass flow rate on number mean density. There is a slight optimum noted around 1.5 g/s xenon. This could be spurious, however, with such data spread. Increasing the mass flow rate decreases the arc impedance. Therefore the arc power decreases with increasing flow rate. The power ranged from 2.9 to 2.0 megawatts for the cases shown.

Plasma arrival time at $Z = 30$ is also shown in table I. This is when the initial plasma light is detected at that station.

The mass flow rate affects the noise in the voltage signature as shown in figure 5. The noise is greatest for 0.5 g/s case. As the mass flow rate is increased, the power decreases, as does the voltage amplitude, and the noise. For the 0.5 g/s case, the data at $r = -2$ and +4 cm were such that less than 50 percent of the shots recorded had desirable number density values. The data were not tabulated in table I because of the poor statistical sample. The noise on the voltage trace for that case combined with poor shot to shot reproducibility might be connected to explain the inability to obtain meaningful number density values. The other blank spaces in table I also indicate poor statistical samples. Here presumably noise was not the factor but rather poor shot-to-shot reproducibility of the exhaust.

The square wave current drive for the arc is also shown. As the mass flow rate changes, a slight mismatch of the arc impedance compared to the PFN bank impedance causes some unwanted current reflections after 150 microseconds.

CONCLUDING REMARKS

The exhaust of a gas-fed megawatt plasma source was surveyed to see if it might be a suitable medium for pumping a charge-exchange laser. It found suitable, the source could be used to evaluate a proposed near-resonant charge exchange pumping mechanism. This mechanism could produce a near ultraviolet stimulated emission with sufficient gain. It required a xenon plasma of approximately 10^{14} cm^{-3} number density and 2-3 eV electron temperature. This plasma was to be seeded with calcium.

The results of the present experimental work show that at 30 cm downstream from the source, there is at least an 8 cm diameter exhaust with number density in the low 10^{13} cm^{-3} range and 4 to 8 eV electron temperatures for the 1.5 g/s xenon flow rate case. After the transient spike at the beginning of the plasma event, the densities and temperature of this order presist for over 80 microseconds.

The xenon exhaust at the Z = 30 cm station has properties that are minimal to evaluate the theory. The electron densities are an order of magnitude less than required to make a suitable gain measurement and the electron temperature are 2 to 3 times too large. The electron temperature is critical to successful inversion. If the electron temperature is too high it overpopulates the lower lasing level, thus spoiling the inversion.

To obtain the proper exhaust conditions, the number density should be increased and the electron temperature decreased. Methods to accomplish this goal are being investigated. The plasma source might have to have its exhaust contained (mechanical or magnetic nozzling) to increase the density. Another approach being examined is to increase the mass flow rate of the source significantly to obtain high densities of exhaust. This, in conjunction with moving closer to the source, might produce a suitable xenon exhaust. Although the present power supply is limited, increasing the driving current as well as the mass flow rate is also a possible method to increase the density.

REFERENCES

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6. Posta, S. J., and Michels, C. J., "20 Kiloampere PFN-Capacitor Bank with Solid-State Switching," Rev. of Scientific Instrs., Vol. 44, No. 10, Oct. 1973, p.

TABLE 1. - TYPICAL EXHAUST CHARACTERISTICS

(16 kA, 3.5 MS COLD FLOW UNTIL ARC "ON", Z = 30 CM, AFTER INITIAL TRANSIENT SPIKE)

FLOW RATE, g/s Xe	ARC POWER, MW	RADIUS, CM	PLASMA ARRIVAL TIME, μSEC	ELECTRON TEMPERATURE		ELECTRON NUMBER DENSITY		
				MEAN VALUE, eV	EXTREME VALUES, eV	MEAN VALUE, CM^{-3}	EXTREME VALUES, CM^{-3}	
0.5	2.9	-2	40	--	- --	--------	--------	--------
		0		4	3, 22	1.4×10^{13}	4×10^{12}	1.6×10^{13}
		+2		4	4, 12	3.2×10^{13}	2.8×10^{13}	5.0×10^{13}
		+4		--	- --	--------	--------	--------
1.5	2.2	-2	53	--	- --	--------	--------	--------
		0		7	3, 20	1.7×10^{13}	7.0×10^{12}	1.8×10^{14}
		+2		10	4, 16	5.4×10^{13}	2.6×10^{13}	4.0×10^{14}
		+4		3	2, 4	1.0×10^{13}	4.0×10^{12}	3.6×10^{13}
2.0	2.2	-2	60	4	3, 7	1.5×10^{13}	9.0×10^{12}	2.7×10^{13}
		0		-	- --	--------	--------	--------
		+2		4	- --	2.3×10^{13}	1.9×10^{13}	3.2×10^{13}
		+4		-	- --	--------	--------	--------
3.5	2.0	-2	65	4	1, 12	1.7×10^{13}	1.0×10^{13}	2.5×10^{13}
		0		5	2, 21	1.1×10^{13}	5.0×10^{12}	1.0×10^{14}
		+2		4	- --	3.0×10^{13}	--------	--------
		+4		4	- --	4.0×10^{12}	--------	--------

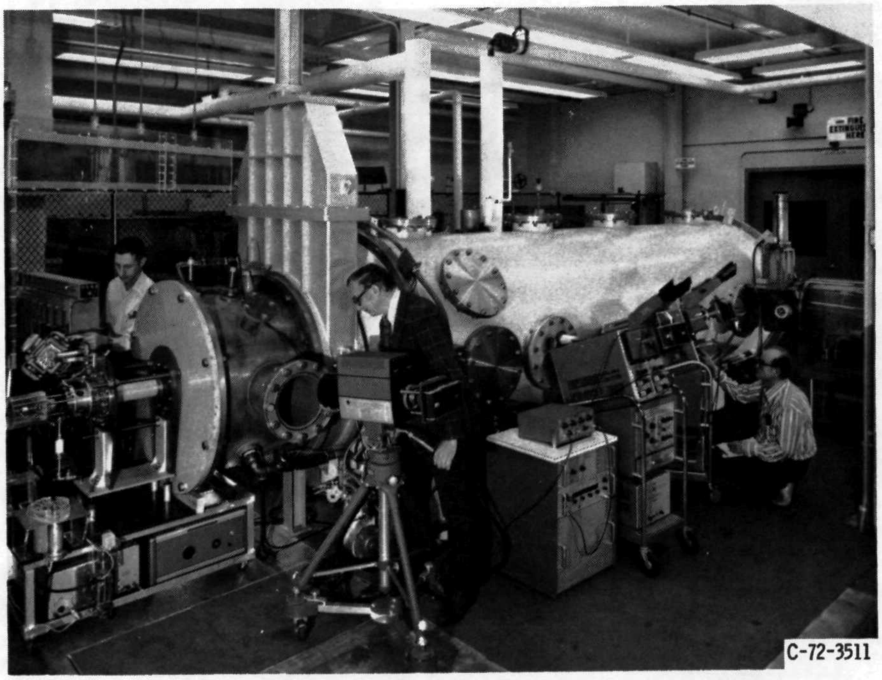
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Figure 1. - New vacuum facility.

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		+2		4	4, 12	3.2×10^{13}	2.8×10^{13}	5.0×10^{13}
		+4		--	- --	--------	--------	--------
1.5	2.2	-2	53	--	- --	--------	--------	--------
		0		7	3, 20	1.7×10^{13}	7.0×10^{12}	1.8×10^{14}
		+2		10	4, 16	5.4×10^{13}	2.6×10^{13}	4.0×10^{14}
		+4		3	2, 4	1.0×10^{13}	4.0×10^{12}	3.6×10^{13}
2.0	2.2	-2	60	4	3, 7	1.5×10^{13}	9.0×10^{12}	2.7×10^{13}
		0		-	- --	--------	--------	--------
		+2		4	- --	2.3×10^{13}	1.9×10^{13}	3.2×10^{13}
		+4		-	- --	--------	--------	--------
3.5	2.0	-2	65	4	1, 12	1.7×10^{13}	1.0×10^{13}	2.5×10^{13}
		0		5	2, 21	1.1×10^{13}	5.0×10^{12}	1.0×10^{14}
		+2		4	- --	3.0×10^{13}	--------	--------
		+4		4	- --	4.0×10^{12}	--------	--------

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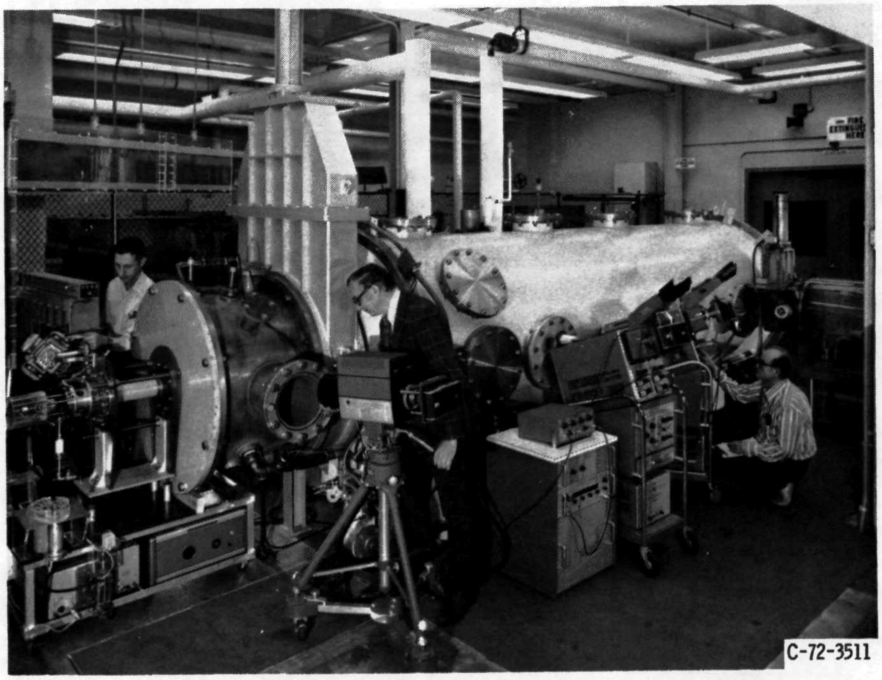


Figure 1. - New vacuum facility.

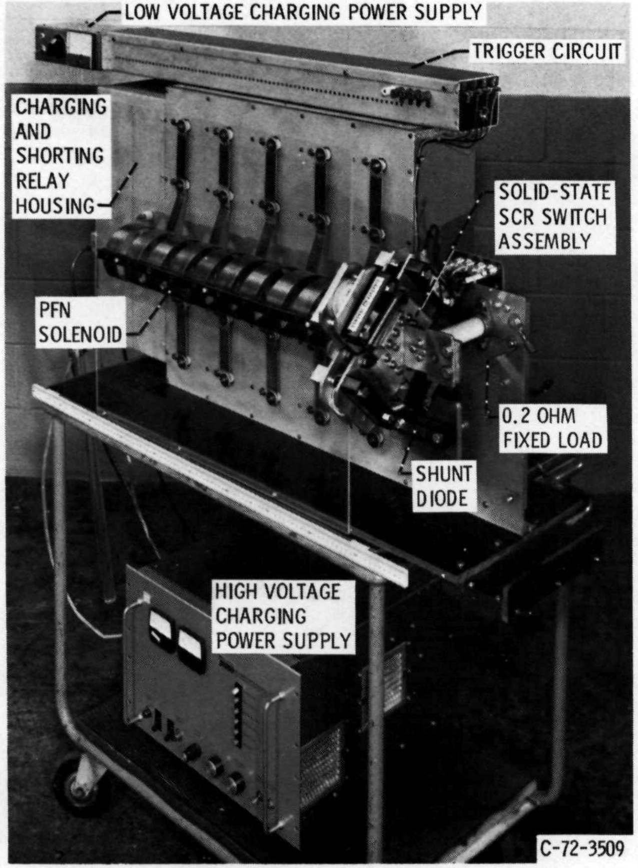
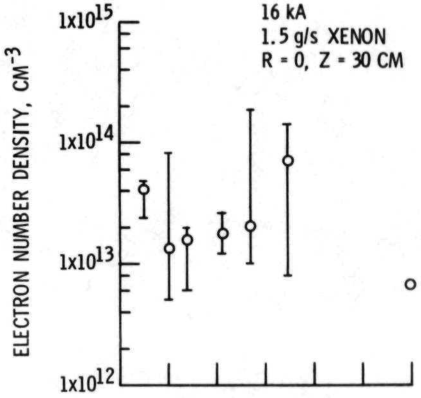
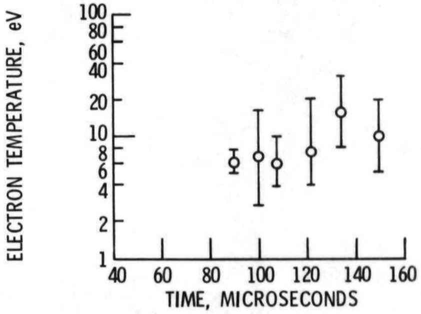


Figure 3. - Pulse forming network - capacitor bank.

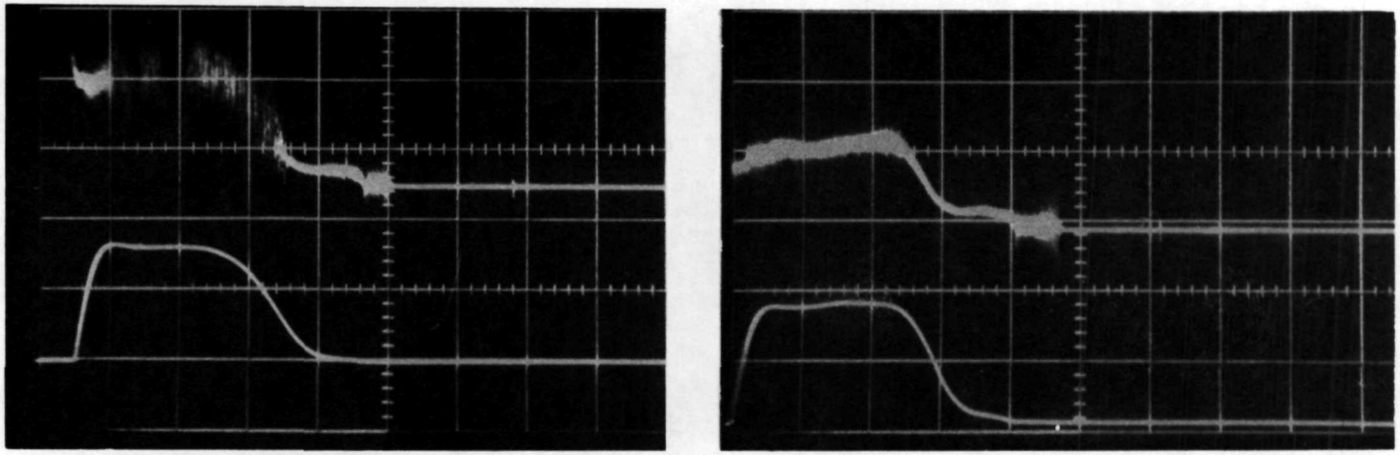


(A) ELECTRON NUMBER DENSITY.



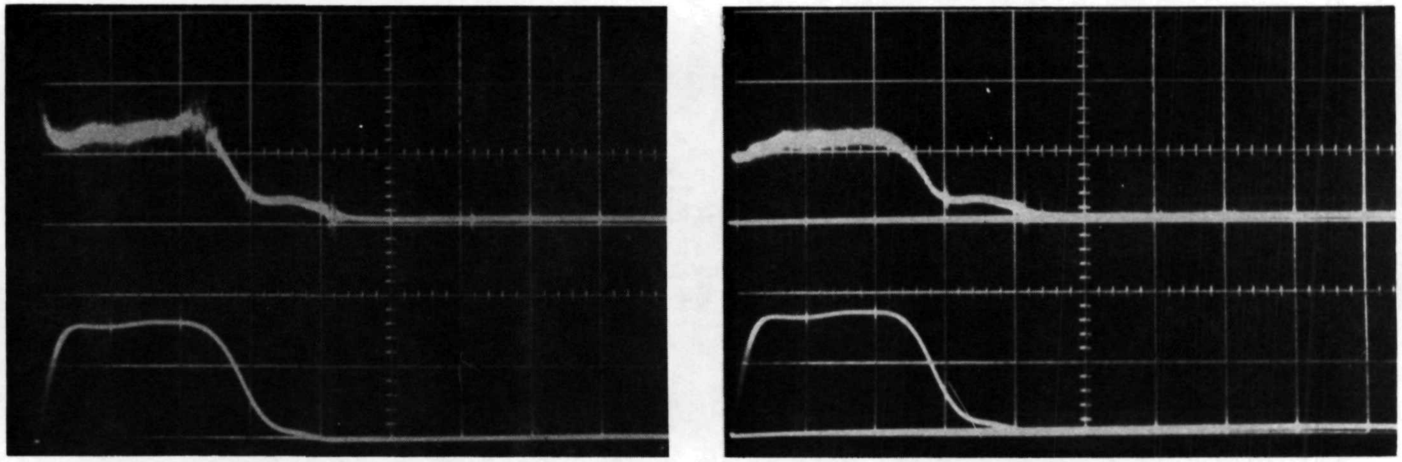
(B) ELECTRON TEMPERATURE.

Figure 4. - Temporal variation of exhaust.



(a) 0.5 g/s XENON.

(b) 1.5 g/s XENON.



(c) 2.0 g/s XENON.

(d) 3.5 g/s XENON.

Figure 5. - Typical arc voltage and current traces. Horizontal, 50 μsec/cm; verical (upper trace), 100 V/cm; vertical (lower trace), 10 kA/cm.