

# Exhaust Characteristics of a Megawatt Nitrogen MPD-ARC Thruster

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The number density ( $n_e$ ), electron temperature ( $T_e$ ), and velocity of the exhaust of a single pulse thruster were experimentally determined for various applied axial magnetic fields (0, 1.0, and 2.0 T). At an axial station 0.2 m from the anode, the no-field exhaust profile is approximately constant up to 4.0 cm from the centerline,  $n_e = 1.0 \times 10^{21}$  p/m<sup>3</sup>,  $T_e = 7.2$  eV. At 1.0 and 2.0 T, centerline  $n_e < 10^{21}$  p/m<sup>3</sup> and the  $n_e$  raises to a maximum of  $1.0 \times 10^{21}$  p/m<sup>3</sup> and  $0.6 \times 10^{21}$  p/m<sup>3</sup> respectively at a radius of 2 cm. Corresponding velocities ( $0.2 \rightarrow 0.8 \times 10^4$  m/sec) were measured and are discussed.

## Introduction

STUDIES at Princeton University,<sup>1-5</sup> Langley Research Center,<sup>6</sup> Lewis Research Center,<sup>7,8</sup> University of California, San Diego,<sup>9</sup> General Dynamics Corp.,<sup>10</sup> Avco Corporation,<sup>11</sup> and Geotek Inc.<sup>12</sup> have been made of various details of pulsed, MPD-ARC thruster operation. Single shot, megawatt level operation was described in Refs. 1-5 for the self-field case, the thruster being powered by a delay-line capacitor bank.

The investigation at Lewis Research Center of single shot, pulsed, megawatt level, MPD-ARCs has been initially reported by Michels.<sup>7,8</sup> These reports<sup>7,8</sup> describe terminal characteristics for the auxiliary magnetic field case, the thruster being powered by a crowbarred capacitor bank. The arc current decays with time and with this type power source. A portion of the detailed investigation described by Jahn et al.<sup>3</sup> gives the number density and temperature for one self-field case. These are obtained with a local probe in direct contact with the plasma. Herein, plasma diagnosis through Thomson scattering is used as an independent and direct method of obtaining number density and electron temperature for various values of auxiliary magnetic field. The technique of determining number density and electron temperature from Thomson scattering of the beam of a Q-spoiled ruby laser is now well established.<sup>13,14</sup> The combination of low electron temperature (a few electron volts) and low number density (approximately  $10^{20}$  particles per cubic meter) have been the criterion that determined the simple, yet judiciously designed, two-channel, 90° scattering system used in this experiment.

## Apparatus

### Plasma Accelerator

The plasma source was energized by a 10 kilojoule bank described in Ref. 8. The bank was crowbarred to provide an almost linear decay of arc current for about 100  $\mu$ sec after crowbaring and it is during this period that the data was gathered. A superconducting magnet system is used to provide the auxiliary magnetic field.

A cross-sectional view of the arc chamber is shown in Fig. 1. An iron filings map of the magnetic field is also shown. The

cathode is a tungsten ribbon measuring 1 cm wide, 2 cm long, and 1 mm thick. The anode is a 4.2-cm-i.d. copper ring.

Nitrogen propellant was introduced into the arc chamber by a high-speed gas valve that was operated by an electromagnetic actuator. All tests were run at 7 g/sec nitrogen. The transient, cold flow, gas pressure in the arc chamber was measured by a commercially available piezoelectric pressure transducer in a previous experiment. That pressure and the orifice equations for steady flow were used to calculate the mass flow rate for all the tests of this report. From the transient pressure records it was found that stable flow occurred after 650  $\mu$ sec. The arc was started at that time. Thereafter, a transient plasma flows for a few hundred microseconds into the evacuated glassware section.

A sequence controller controls gas puff injection, delay for gas distribution, bank switch closure, crowbar switch closure, and then data gathering "start" and "stop" times.

## Instrumentation

### Thomson scattering

Figure 2 gives the schematic of the laser diagnostic equipment and its relationship to the plasma test section. The laser was a Q-switched ruby with 2 joules output. The portion of the light measured was that which was scattered in a direction normal to the plane of polarization of the laser beam (i.e., 90° Thomson scattering). To minimize the stray light entering the detection system a series of light stops were placed along the path of the incoming beam and two light dumps were used. One light dump (no. 1) serves as a dump for the main beam, and the other (no. 2) serves as a black background for the scattered light detection system. The Doppler-shifted scattered light was analyzed through the use of a two-channel interference filter system similar to that of Patrick.<sup>15</sup> The photomultipliers are EMI 9558B's. Each channel has a filter holder containing up to seven filters which can be easily changed. In the experiment the scattering parameter  $\alpha = [\lambda / (4\pi\lambda_D \sin\theta/2)]$  is much less than one ( $\approx 0.1$ ).  $\lambda$  is the laser wavelength and  $\lambda_D$  the Debye distance. Theoretically then, if a Maxwellian electron velocity distribution is assumed, single-shot data from two filters with different peak wavelengths is sufficient to determine the temperature. Using the available transmission curves for the interference filters the fraction of scattered light passed by each filter was calculated as a function of electron temperature. In taking data the ratios of signals from two different filters were computed for each shot and then a series of five ratios was averaged before determining the temperature.

Temperatures could also be determined by using just one of the channels. In this case ten shot averages were taken for a

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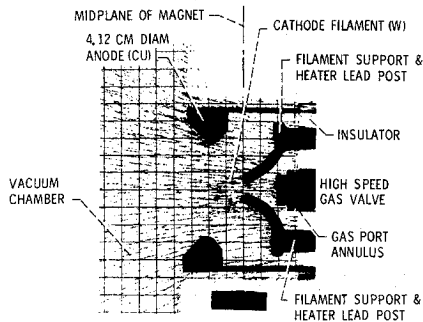


Fig. 1 Arc chamber.

series of six filters ranging in peak wavelength from 694.3 to 697.8 naut miles. A best fit was then made of the theoretical curves to determine the temperature. Figure 3 shows a comparison of theoretical and a typical experimental profile. It was found that temperatures obtained through the two methods agreed within the limits set by nonreproducibility of the discharge and other statistical factors.

Most of the data herein was taken using the two-channel method, since fewer shots were needed. There was also the added advantage that signal ratios taken from the same laser shot and plasma discharge were more accurate than those derived from two separate shots.

The system was calibrated for density by measuring the Rayleigh scattered light when the test section was filled with nitrogen at a few millimeters pressure. The shot to shot variation in the calibration signals was less than  $\pm 10\%$ .

For scattering from the plasma, shot to shot variations ranged from  $\pm 10$  to  $\pm 30\%$ . Examination of other diagnostics such as light emitted from the plasma and Faraday cup signals indicates that this shot to shot variation in Thomson scattering can be explained by the nonreproducibility of the discharge.

The lower limit in density which could be accurately determined in this experiment was about  $0.5 \times 10^{20} \text{ m}^{-3}$ . This limit occurs because of the noise on the photomultiplier signal resulting from the light emitted by the plasma. This limit can obviously be reduced by the use of a higher powered laser. Figure 4 shows typical two-channel scattered light signals.

#### Faraday cup probe

A Faraday cup probe was used to collect ions from the streaming plasma simultaneous with scattered light data gathering. A pinhole at the front of the probe was used as a mechanical aperture to limit the influx of neutral flowing

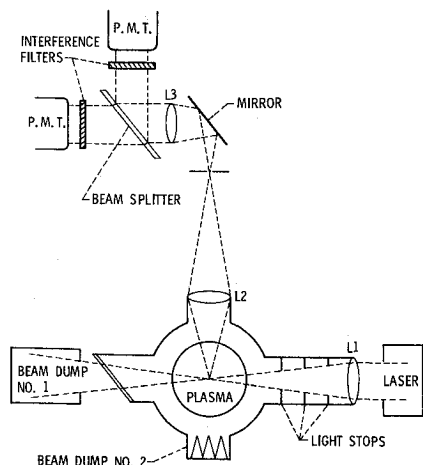


Fig. 2 Schematic of scattering diagnostic equipment.

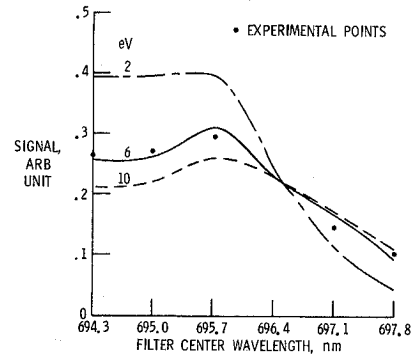


Fig. 3 Theoretical and experimental spectral profiles.  
 $T_e \approx 6 \text{ eV}$ ,  $n_e \approx 1 \times 10^{21} \text{ m}^{-3}$ .

plasma into the probe. This pinhole was not used as an electrical stripping screen hole. The probe shell and cup were electrically floating. Once the plasma had penetrated the pinhole it was subjected to a 45 v differential voltage between the cup and the shell inside conducting wall. This allowed the cup to collect only all the ions that came through the pinhole. The probe face was kept 10 cm downstream from the scattering measuring station so as not to introduce stray light signals in the scattering chamber. The probe could be positioned to be on the same duct radius as the scattering measurement. Pinholes could be changed on the probe face (0.0002 m diam or 0.00074 m diam). Instrument isolation amplifiers with excellent common mode rejection were employed. In order to obtain isolation and good common mode rejection instrument response time was compromised at 15  $\mu\text{sec}$  rise time. Thus the leading edge and fine detail of the cup signal were not available in this experiment. Since collected ion current is proportional to pinhole area, a check was made to insure that this was the case by changing hole size. This proved to be linear.

#### Results and Discussion

The value of a direct method of determining number density through Thomson scattering was demonstrated clearly in the early stages of this experiment. It was found that minor changes in the insulator design near the cathode in the chamber (all other dimensions and materials remaining the same) seriously affected the exhaust number density. Factors of two to three increase in number density were obtained by fully insulating the cathode supports. This forced the discharge to be initiated and seated at the cathode ribbon. In earlier designs, a very minor arcing damage was noted on the cathode supports. This probably occurred only briefly in random arc initiations. In this report, only the data for the most improved version will be described.

The precise temporal and spatial resolution of the Thomson scattering technique identified another feature of the exhaust. Shot to shot variations in number density and temperature were serious. The variations in the manner of initiation and development of the arc thus were observable as ex-

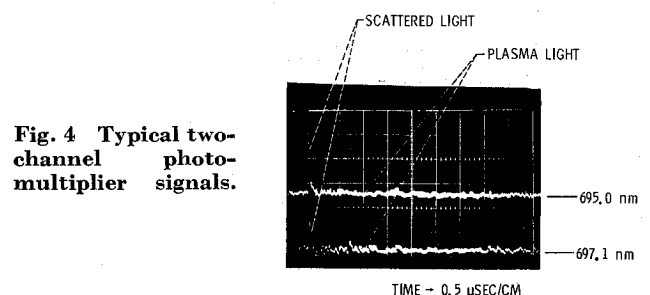


Fig. 4 Typical two-channel photo-multiplier signals.

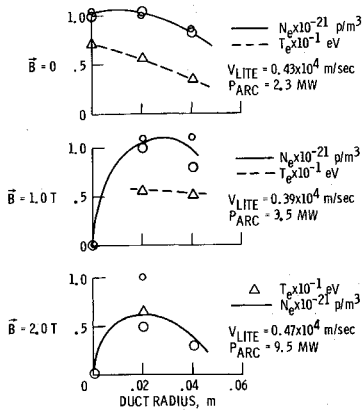


Fig. 5 Exhaust characteristics.

haust variations. The data presented is the mean value of at least five shots for each condition.

The exhaust flowed from the source into a 15-cm-diam evacuated glassware duct. A detailed examination of the exhaust was undertaken at a station 20 cm downstream from the anode face. The number density and electron temperature profiles were measured at the station for various auxiliary magnetic field cases (0, 1.0, and 2.0 T). The results are shown in Fig. 5 for the case where peak arc-current for each shot is 13.4 ka. All shots had the same mass flow rate (7 g/sec  $N_2$ ), and the same gas settling time of 650  $\mu\text{sec}$ . The data was taken about 20  $\mu\text{sec}$  after the plasma light front had reached the measuring station. This time was chosen so that initial transient effects would be small and the measurement would be in the streaming plasma portion of the flow.

The time history of the plasma light passing the measuring station has a general shape shown below in Fig. 6. Shot to shot this shape varies, sometimes the pedestal portion is distinct, at other times it is part of the smoothly decaying tailoff portion. Generally, the spike portion has less number density by at least an order of magnitude. The pedestal has  $N_e$  values in the range of  $10^{20}$ – $10^{21} \text{ m}^{-3}$  and the tail portion has lower and time-decaying values. Moving the measurement time later (to 60–70  $\mu\text{sec}$  on the sketch) quite often showed factors of two reduction in number density. This is to be expected since during that corresponding time the arc power is reducing also by like factors due to the decay in arc current.

With these general characteristics understood, the data of Fig. 5 can now be discussed. For the case of no auxiliary field, the number density is  $1.0 \times 10^{21} \text{ m}^{-3}$ . The density profile was nearly constant from duct centerline to 4 cm radius. The electron temperature falls linearly from a centerline value of 7.3 eV to 3.5 eV (4 cm). The arc power was 2.3 Mw at 36  $\mu\text{sec}$  after the arc was initiated. That is 15  $\mu\text{sec}$  after the crowbar time. The number density profile was much different for the cases where an auxiliary magnetic field is employed. Over an order of magnitude reduction in density occurs on centerline for both the 1.0 and 2.0 T cases. The peak density occurs at a radius of 2.0 cm. At the 2 cm radius for the 1.0 T case, the number density was still about  $1.0 \times 10^{21} \text{ m}^{-3}$  but for the 2.0 T case it reduced to  $0.6 \times 10^{21} \text{ m}^{-3}$ . For the 2.0 T case, the arc power was 9.5 Mw, at 36  $\mu\text{sec}$  after the arc was initiated, over four times greater than the no-field case. This power increase was not manifest by

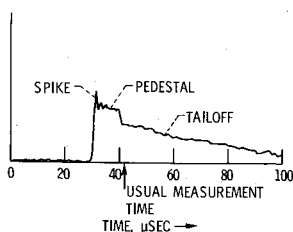


Fig. 6 Typical plasma light time history.

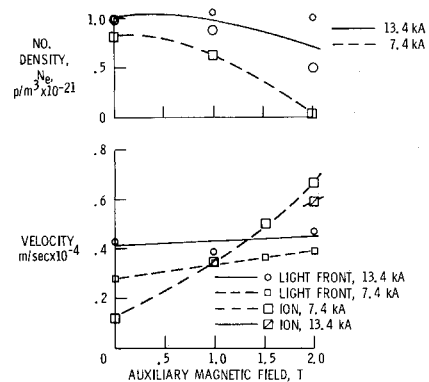


Fig. 7 Exhaust characteristics vs magnetic field at  $r = 0.02 \text{ m}$ ,  $z = 0.2 \text{ m}$ .

number density increase, nor electron temperature increases from the no-field case, in fact, the density reduced! With these facts, the next logical exhaust characteristic, velocity, was measured.

The time of arrival of the light front at the measuring station was used to determine the velocity,  $V_{\text{LITE}}$ , shown in Fig. 5. This is an indicator of light front behavior only and not necessarily ion velocity after the front has passed. For the no-field and 1.0 T cases,  $V_{\text{LITE}}$  were alike, within measurement error at about  $0.4 \times 10^4 \text{ m/sec}$ . The velocity for the 2.0 T case was 10% greater. This would not be a great enough increase for the power increase to be explained as increased streaming energy.

An attempt was made to obtain ion velocity through the use of a Faraday cup. At the 13.4 ka peak current case, only one condition was examined successfully. This was because at higher power levels the ratio of the common mode signal (to the measurement signal) could not be reduced enough. From the one successful cup measurement at 13.4 ka and the corresponding number density, the ion velocity  $V_i$  was found to be  $0.58 \times 10^4 \text{ m/sec}$ . This prompted investigation of a lower power level regime where the cup could be used successfully.

At the lower power regime (7.4 ka peak arc current) the measurements were made at  $r = 2 \text{ cm}$  (where  $N_e$  is the greatest value). The data are shown for the 7.4 ka peak current case in Fig. 7 and the 13.4 ka data is included for comparison. The number densities were lower for the 7.4 ka case, as are the front velocities. Ion velocities, from the Faraday cup measurements, showed a six-fold increase as the field is increased from 0 to 2 T. Thus, at this power level, the ion velocity increase comes closer to being proportionate to the observed power increase. Again, as for the 13.4 ka cases, it was found that  $V_{\text{LITE}}$  increased slightly with applied magnetic field. Thus  $V_{\text{LITE}}$  is only an indicator of front ar-

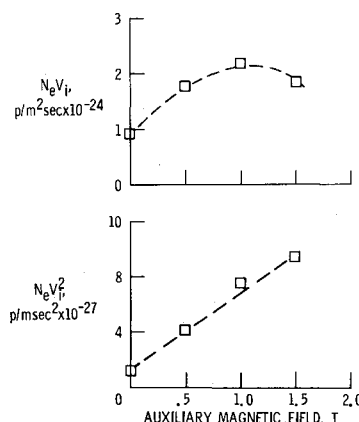


Fig. 8 Exhaust  $N_e V_i$  and  $N_e V_i^2$  vs magnetic field strength at  $r = 2 \text{ cm}$ ,  $z = 0.20 \text{ cm}$ , 7.4 ka.

rival effects and not the streaming ion flow component of the exhaust.

The product  $N_e V_i$  should indicate the exhaust momentum for that station and time. This product, when plotted versus applied magnetic field (see Fig. 8) peaks at about 1.0 T for the data of Fig. 7.

The product  $N_e V_i^2$  should be proportional to dynamic stream pressure. For the data of Fig. 7,  $N_e V_i^2$  is almost linearly increasing with applied magnetic field. It is planned, in the near future, to examine, with an independent measurement of dynamic pressure, if the pressures obtained agree with the Faraday cup derived pressure calculations.

### Concluding Remarks

The number density and electron temperature of the exhaust of a pulsed megawatt MPD-ARC plasma thruster were determined for two different peak arc-current cases (13.4 ka and 7.4 ka) for various values of auxiliary magnetic field (0. to 2.0 T). The radial profile of the exhaust was obtained for a position 20 cm downstream from the anode face. For the 13.4 ka case, with no auxiliary field, the centerline number density was  $1 \times 10^{21} \text{ m}^{-3}$  and was relatively flat out to 4.0 cm radius. For the applied field cases the centerline number density is reduced to below  $10^{20} \text{ m}^{-3}$  and peaks at 0.02 m radius. At the 2 cm radius location, for the 1.0 T case the number density is still about  $1.0 \times 10^{21} \text{ m}^{-3}$  but as field is increased above this point number density reduces. At 2.0 T the number density is down to  $0.6 \times 10^{21} \text{ m}^{-3}$ . An electron temperature range from 7.3 to 3.0 eV was noted. Using the Thomson scattering technique is a very powerful aid in examining high-density exhaust. It gives local  $N_e$  and  $T_e$  directly without auxiliary methods or assumptions and with excellent temporal and spatial resolution without perturbing the plasma.

The same degree of confidence cannot be applied to the velocity measurements discussed herein. These suffer the usual probe-in-plasma uncertainties. The Faraday cup derived velocities determined for the 7.4 ka range from 0.1 to  $0.68 \times 10^4 \text{ m/sec}$ . The probe perturbs the plasma an unknown degree, has the attendant particle gathering problems, and cannot be used in very high power, extended pulse duration, exhausts.

The temperature measurements for the no-field and field cases show that increasing arc power through the aid of a passive externally applied, magnetic field does not increase electron heating. Instead, the increased power from the no-

field case to field cases seems to result primarily in increased plasma streaming energy. More work needs to be done to verify this through another independent velocity measurement, over more stations and at higher power.

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