Electron Number Density and Temperature in MPD-Arc Thruster Exhausts

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Theme

THE electron number density and electron temperature of the exhaust of a pulsed, megawatt, MPD-Arc thruster are measured at a station located 30 cm downstream of the thruster throat. The measurements are taken every 10–20 μsec for a period of approximately 100 μsec after the plasma exhaust arrives at the measuring station. Measurements are made for various sets of thruster parameters. The mean deviation of the data scatter is presented to show the nature of the exhaust variation. The data is compared with earlier work at a measuring station closer to the thruster so as to define the nature of the exhaust expansion with and without a thruster auxiliary magnetic field.

Contents

The measurement of electron number density and electron temperature at increments of time through the major portion of the exhaust flow was taken because the data serves multiple purposes. The prime purpose is that local number density combined with other diagnostic data[1] (such as impact pressure) provide thruster values of local exhaust velocity and mass flow rate. Another purpose is that since the experiment is a high-power test for plasma exhausting in a diverging magnetic nozzle, the number density and temperature are useful in understanding the nozzle expansion process. Finally, there is a need to know the temporal variation of these variables because all of the megawatt level research is performed in the pulsed mode. The question of how long it takes to obtain steady (or quasi-steady) conditions in the thruster and exhaust must be resolved if the data are to be compared with steady-state theory.

The thruster[1,2] was energized by a 10 kjoule capacitor bank that was crowbarred at peak current to provide a monatonic decay of arc current for 500 μsec. A superconducting magnet provides the auxiliary magnetic field (0–2.0 T). Nitrogen propellant was introduced into the propellant chamber by a high-speed gas valve. After allowing a 650 μsec settling time, the cold gas flow rate is 3.0 g/sec. The arc is initiated at that time and a transient plasma flows for a few hundred microseconds into the evacuated 15-cm-diam glassware exhaust duct. The electron number density and electron temperature are measured[2] by illuminating the exhaust plasma with a pulsed laser light source and measuring the 90° scattered light intensity and spectral broadening (Thomson-scattering).

The local variations in number density (n_e) and temperature (T_e) simply detected by this method show up as significant data scatter (large mean deviation). Figure 1 shows the average value of n_e and T_e in the exhaust, along with their respective mean deviations, for a particular station (duct radius, $R = 4$ cm, and axial distance from the anode face, $Z = 30$ cm), and for a particular peak current, 20 ka. Each data point of the figure presents the mean value of 10 separate shots. The limit of detectability of the electron number density for the measuring system is $1.0 \times 10^{19}\,m^{-3}$. Any plasma that arrives earlier than the earliest data point in the figure has less density than this detectable limit. Data are shown beginning at 76 μsec and measured at intervals of about 10 μsec out to about 200 μsec. Detectable data exist beyond this time but, for practical reasons, the temporal survey was stopped at 200 μsec. Exhaust pressure histories[1] show the interval of interest is complete by then.

Figure 1a displays the data for an auxiliary magnetic field of 1.0 T. The mean value of n_e is surprisingly constant, $8 \times 10^{19} m^{-3}$, from 76 to 200 μsec. T_e ranges from 4 to 6 ev during this period of time and the mean deviation is large. Purposely, a curve through the mean value was not attempted, because it would not accurately reflect the temporal behavior of a particular shot. The large mean deviation reflects significant fluctuations in the exhaust when examined with the 0.2 cm^3 spatial resolution instrument. This is in sharp contrast to expected shot to shot

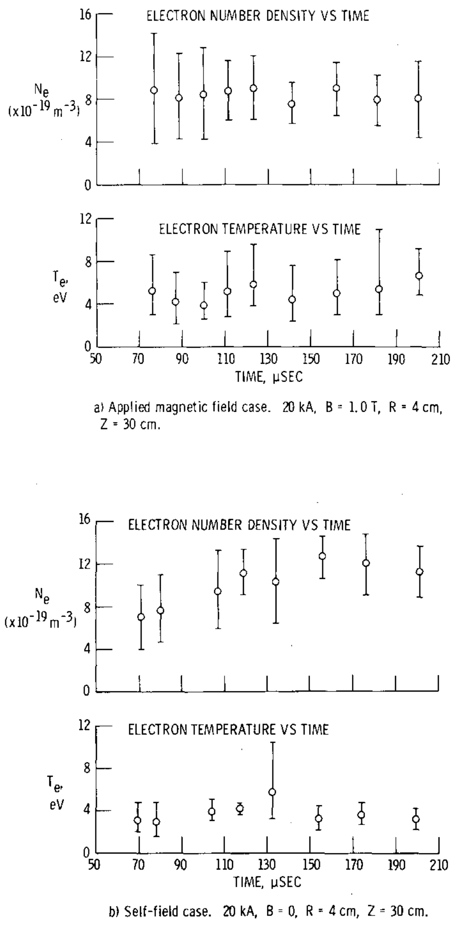

Fig. 1 Temporal exhaust characteristics.

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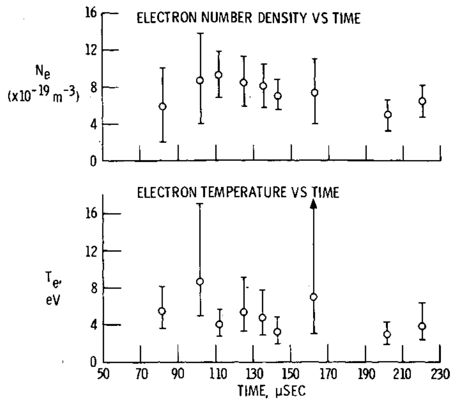

Fig. 2 Temporal exhaust characteristics. (11.2 ka case, $B = 1.0$T, $R = 4$, $Z = 30$ cm).

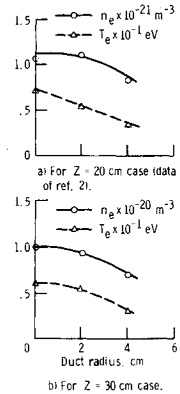

Fig. 3 Exhaust characteristics. 20 ka, self-field case.

repeatability of gross phenomena like terminal characteristics and impact pressures[1] (measured with larger probe faces). Arc current and impact pressure are decaying with time; yet the mean value of n_e is found to be relatively constant. This is probably the result of the magnetic nozzle action and the influence of the duct walls.

For the corresponding case with no auxiliary magnetic field (Fig. 1b), the T_e is lower, 3–4 ev, and the mean deviation is lower. This is a lower powered case. At lower temperatures, the ratio of scattered light to plasma light (signal to noise ratio) is larger. Thus the data are less subject to readability and interpretational errors. The mean value of n_e increases with time and even goes above the $B = 1.0\,T$ case of Fig. 1a to values of 10 to 12×10^{19} cm^{-3}.

If the peak arc current is reduced to 11.2 ka, the data for conditions corresponding to Fig. 1 are lower and have larger mean deviations. With an auxiliary magnetic field of 1.0 T, n_e is above the detectable limit, but the relatively small signal to noise ratio makes the raw data difficult to interpret. This is reflected in the large mean deviations shown in Fig. 2.

For a peak arc current of 20 ka and no auxiliary magnetic field, data were obtainable at all three radial stations ($R = 0$, 2 and 4 cm). The temporal behavior of n_e and T_e at $R = 0$ and 2 cm is much like the data shown in Fig. 1b for $R = 4$ cm. To simplify the discussion of radial profiles of n_e and T_e, consider a particular time, the time of first detectable plasma arrival. In Fig. 3a, these profiles are shown for the $Z = 20$ cm station,[2] and in Fig. 3b, these profiles are shown for the $Z = 30$ cm station. The radial profile shapes are generally the same for n_e and T_e at either station. The value of n_e is almost an order of magnitude less at the downstream station ($Z = 30$ cm), showing the effect of expansion for the self-field case. The electron temperature remains almost the same value for either station. The electron thermal conduction down the exhaust plume is sufficient to keep most of the exhaust plume at roughly a uniform temperature.

For an auxiliary magnetic field of 1.0 T and a peak arc current of 20.0 ka (Fig. 1a), the only detectable data are at $R = 4$ cm at the $Z = 30$ cm station. The number density was again about an order of magnitude less than at the $Z = 20$ cm station. The electron temperature was about the same as at $Z = 20$ cm (but at $R = 2$ cm), showing the effect of high thermal conductivity along expanding magnetic field lines in the nozzle. The electron number density for the 1.0 T case was a maximum at $R = 2$ cm at $Z = 20$ cm. At $Z = 30$ cm, the electron number density is detectable only at $R = 4$ cm. This shows that the maximum in n_e moves farther from the axis with increasing distance from the engine throat. The "hole" in the n_e radial profile described in Refs. 1 and 2 is expanding with the expanding magnetic field.

The surprisingly constant (or even slightly increasing) average n_e and T_e values noted in this experiment does not mean that one can conclude anything about the conditions being quasi-steady or not until other measurements are examined. Arc current is decaying with time and impact pressure is decaying in the same manner as arc current. The effect of the narrow exhaust duct, the cold gas flow preceding the plasma flow, and the unknown time constants for the arc chamber-arc plume flow stabilization all affect the understanding of the time varying exhaust measurements.

References

[1] Michels, C. J. and York, T. M., "Exhaust Flow and Propulsion Characteristics of a Pulsed MPD -Arc Thruster," AIAA Paper 72–500, New York, 1972.

[2] Michels, C. J. and Sigman, D. R., "Exhaust Characteristics of a Megawatt Nitrogen MPD-Arc Thruster," *AIAA Journal*, Vol. 9, No. 6, June 1971, pp. 1144–1147.