Interferometric Density Measurements in the Arc of a Pulsed Plasma Thruster

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Theme

IT is shown how the exhaust density can be measured in pulsed electric thrusters using a multiple-pass optical interferometer. To interpret the data, a theory of the collision free expansion of the arc is developed. Thermal and drift velocities of the ions are adjustable parameters in the theory, so they can be determined by comparison with experimental data. Once determined, the entire exhaust density profile is determined (in two dimensions).

Contents

Pulsed electric thrusters[1] were first flown on the Lincoln Experimental Satellite, LES-6,[2,3] and are to be the sole propulsion system for stationkeeping and attitude control on the LES-8/9 satellites. An extensive series of diagnostic experiments[4,5] aimed at understanding the physics of the discharge is now ending and attempts to improve the performance of these thrusters using this information have begun.

One of the most important parameters characterizing the plasma in this thruster is the particle density. Along with particle temperatures it determines the plasma pressure in the exhaust and hence determines the gas dynamic portion of thrust. It is also an important parameter for calculating radiation from the exhaust, a calculation of some importance in satellite applications where telemetry antennas pick up this radiation. The details of the density contours in the exhaust are also important for estimating particle deposition rates on various surfaces of the spacecraft.

Previous data on the exhaust, obtained with a microwave interferometer[4] and a Faraday cup,[1] and by spectroscopic analysis,[5] yielded downstream densities (densities below 6×10^{12} per cc could be measured), and average (over species) ion drift velocity and temperature.

To measure densities in the arc, which are on the order of 10^{16} particles per cc, a multiple-pass optical interferometer as first described by Rizzo[6] is required. Several passes through the arc are necessary to produce a measurable phase shift since the arc is only 3 mm thick. The experimental apparatus, a Mach-Zehnder interferometer using a 3 mw He-Ne laser, is shown in Fig. 1.

The plasma density is determined by measuring the light intensity (Poynting Flux) through a pinhole detector. The intensity is

$$I = (\mu_0/4\varepsilon_0)^{1/2}[E_1{}^2 + E_2{}^2 + 2E_1E_2\cos(\beta y + \phi)] \quad (1)$$

where E_1 and E_2 are the electric field intensities of the waves in the reference and plasma arms of the interferometer and β is the y-component of the wavenumber $2\pi/\lambda$. The phase shift ϕ

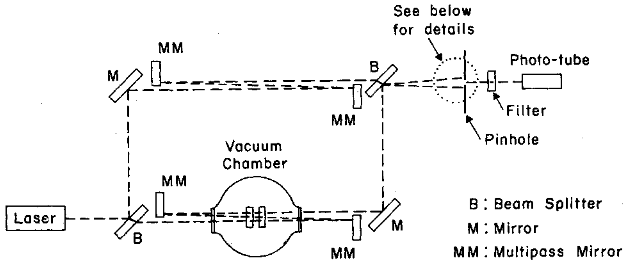

Fig. 1a Schematic of M-Z interferometer with source and photodetector.

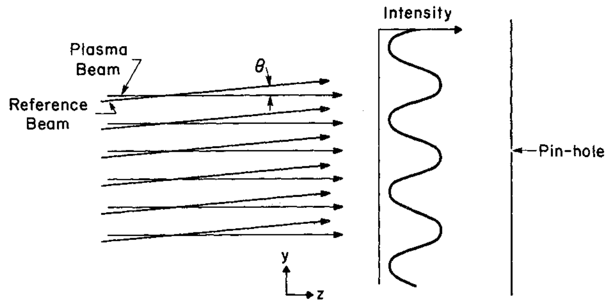

Fig. 1b Expanded view of the recombined beam showing size of pinhole in relation to period of intensity variation.

between the two beams is changed by $\Delta\phi$ when the plasma is introduced. For our parameters,

$$\Delta\phi \approx (2\pi d/\lambda) \cdot n/n_0 \quad (2)$$

with d the total path length (arc width times the number of passes) through the plasma, n the plasma density, $n_0 = 2.78 \times 10^{21}$ particles/cc, and $\lambda = 6328$ Å. (Neutral particles contribute to a phase shift of the opposite sign but of only 1% of the amount for equal electron and neutral densities.)

Data were taken at downstream distances varying from 1 to 26 mm in front of the teflon face. The beam thickness at the arc is less than 2 mm. The results are shown in Fig. 2, which displays the density in time and distance in a variety of ways. To unfold the raw data (phase shift vs time) one uses Eqs (1) and (2) with the plasma thickness and number of passes. The plasma thickness is 3 mm near the arc, but further downstream the exhaust expands with time according to simple thermal expansion. The effective thickness is $\pi^{1/2}v_T t$ with v_T the ion thermal velocity and t the time of interest after the arc initiation. The effective thickness is used starting at ~ 10 mm from the arc and an extrapolation between 3 mm and $\pi^{1/2}v_T t$ is used for $x < 10$ mm. Thermal velocities are known from previous measurements.[1]

From these data and from a theoretical analysis of the expansion of the exhaust come several parameters of importace in a model of the thruster and for understanding the performance limitations of the thruster. To determine these parameters we must first calculate the appropriate plasma distribution function. Earlier analysis[4] assuming a collision-free expansion of the exhaust was experimentally verified by Faraday cup measurements of collected current vs distance along the thrust axis. However, that analysis assumes a point plasma source in time and space, an assumption which is appropriate if comparison

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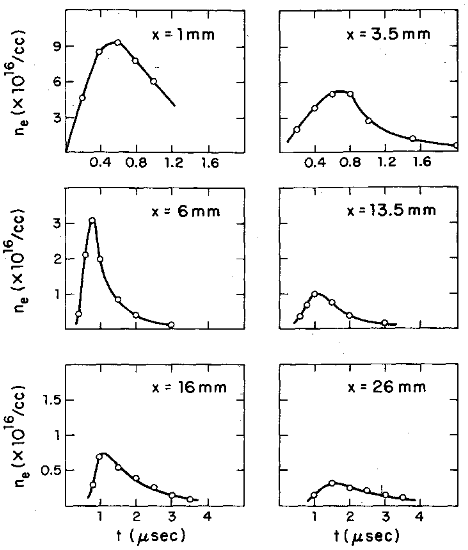

Fig. 2 Curves of measured density as a function of time at various downstream positions.

with measurements is made far from the arc. Near the arc it is necessary to account for the finite time during which the plasma is produced.

The form of the distribution function at some arbitrary plane (labelled $x = 0$) perpendicular to the exhaust axis (x-axis) is assumed to be a drifting Maxwellian.

$$f_0 = An_0(t)g(y)h(z)\exp\{[(v_x - v_0)^2 + v_y^2 + v_z^2]/v_T^2\} \quad (3)$$

The density variation $n_0(t)$ is experimentally determined, but $g(y)$ and $h(z)$ are unspecified functions in the plane. The constant A is determined by integrating f_0 over position and velocity to get the total number of particles.

Now, the downstream distribution function is obtained by the method of characteristics.

$$f = f_0(y - v_y x/v_x,\ z - v_z x/v_x,\ \bar{v},\ t - x/v_x) \quad (4)$$

This solution satisfies the force-free Boltzmann equation, and from it one can determine the downstream density variation (with y, z, and t) given data at $x = 0$. The only difficulty is that g and h are unknown. Approximate solutions can be obtained for planar, line, and point sources by letting g and h be either constants or impulse functions in appropriate combinations. Convolving these solutions with the measured density $n_0(t)$ gives the solutions in the regions where the above sources are representative. The planar source is a good approximation when x is less than the arc height and width, while the line source gives the behavior for x smaller than the arc height ($\sim$2.5 cm). Beyond this the point source approximation is valid, but data could only be obtained to 26 mm with this interferometer, so as previously mentioned the point approximation is of no use to us.

Using the appropriate distribution function we next calculate the current density J_x, which is measured by a Faraday cup, and the total charge Q passing an arbitrary x-plane. Earlier Faraday cup measurements gave $Q = 5.3 \times 10^{-3}$ coul, indicating the exhaust is less than 10% ionized (depending on the fraction of multiply ionized atoms). From our data we find the charge to vary from 21.6×10^{-3} to 9.7×10^{-3} for $x = 3.5$ and 16 mm, respectively. Intermediate x values give intermediate charge values. Thus, the percentage ionization is nearly 4 times larger than earlier measurements. The difference, of course, is either recombination or wall losses as the exhaust moves downstream. This higher percentage indicates that the mass utilization of the thrusters is not as poor as previously assumed.

Further information can be obtained from the densiy data by using upstream data to predict downstream density variations with time. These require numerical convolution within the appropriate region of the assumed source, using proper values of v_T and v_o, the thermal and drift velocities. Thus, these two parameters can be obtained by comparing the predicted and measured densities at several pairs of x-planes. The best fit is obtained with the values

$$v_T = 9.3 \text{ km/sec}, \qquad v_o = 27.9 \text{ km/sec}$$

both of which agree very well with earlier measurements of these parameters from Faraday-cup measurements.

Finally, with the arc density and ion temperature we can determine the partial gas pressure and thruster impulse from the ions. Assuming the ion and electron temperatures and densities are equal ($v_T = 9.3$ km/sec gives an ion temperature of 7.6 ev). The gas dynamic pressure is 4.5×10^5 N/m^2. This pressure acts over 1/3 of the surface (the portion covered by the arc), and since the magnetic pressure is 1.6×10^5 N/m^2 (Ref. 4) the two forces contributed almost equally to the thrust. The conclusion was indirectly confirmed by recent thrust measurements when the mass per shot could be independently varied.[7]

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