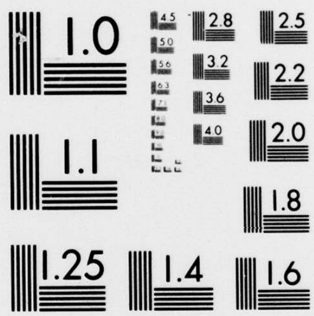
AD-A056 480 ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND FO--ETC F/G 20/5
THERMAL BLOOMING AND AIR BREAKDOWN INTERACTION FOR PULSED HIGH --ETC(U)
JUN 78 R S ROHDE, R G BUSER

UNCLASSIFIED NL

| OF |
AD
A056480

END
DATE
FILMED
8 -78
DDC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

(6)

THERMAL BLOOMING AND AIR BREAKDOWN INTERACTION FOR PULSED HIGH ENERGY LASERS

(11) JUN 1978

(10) *ROBERT S. ROHDE, [redacted].
RUDOLF G. BUSER, [redacted].
US ARMY ELECTRONICS RESEARCH & DEVELOPMENT COMMAND
FORT MONMOUTH, NEW JERSEY 07703

1. Introduction and Problem Definition

Laser pulse transmission as related to Army high energy laser systems involves many interacting effects which generally degrade the performance of the laser systems: molecular absorption, scattering, turbulence, wind, non-linear effects including short and long-time thermal blooming, air breakdown, target-plasma interaction, and optical train jitter. There exists extensive literature on the subject (1-4). This paper deals specifically with the combined effects of short-time (as compared to the acoustic transit time, τ_H, across the beam) thermal blooming and air breakdown.

If both phenomena are present, hot spots in the beam output, as well as the need to produce a plasma at the target for enhanced coupling of energy to the target, will, in many cases, produce statistically random situations which will result in an interplay of breakdown and blooming. One can then ask the following questions: first, in a dynamic breakdown-blooming case, what total energy will be delivered to the target as compared to the breakdown only/blooming-only cases? Second, what will be the average intensity profile in this case. Finally, what role does the temporal beam pulse shape play for optimum energy transfer? Answers to these questions cannot yet be predicted by computer modeling.

As far as experiments are concerned, the two effects so far have been studied only separately (1). The thermal blooming occuring during a laser pulse follows a time evolution referred to as "t^3" in which the on-axis intensity falls as $I \sim t^3$ (5). While there is no loss of energy, there is a loss of intensity as the beam spreads. On the other hand, when air breakdown occurs, the spreading plasma absorbs the beam with resultant loss of energy and, therefore, intensity (2-3). In the following, laboratory simulation experiments combining both effects will be discussed to provide the base line modeling and system prediction.

2. Fundamental Physics Background

A very simple picture of the energy transmission in the presence of both effects can be seen from an examination of the critical times involved in the processes. The on-axis intensity of a pulse beam undergoing thermal blooming will fall to 50% of peak in 1-3 μs for peak intensities of 10^6-10^7 W/cm^2, given the appropriate conditions (absorption, path length, etc.) (see Figures 1 and 2).

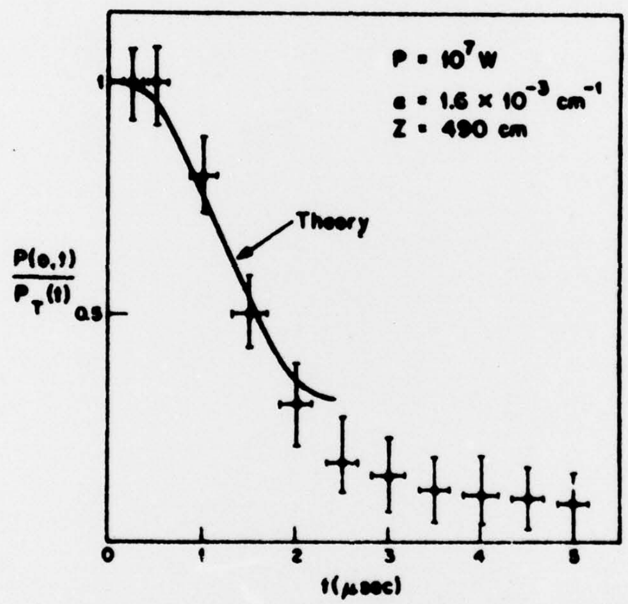


Figure 1. The drop in power due to blooming measured with the aperture located over the peak of the focal distribution has been plotted as a function of time. The theoretical prediction for this case has been plotted for $t < 0.5\ \tau_H$ The length of the absorption cell in the experiments and for the calculation is Z = 490 cm (Ref. 4).

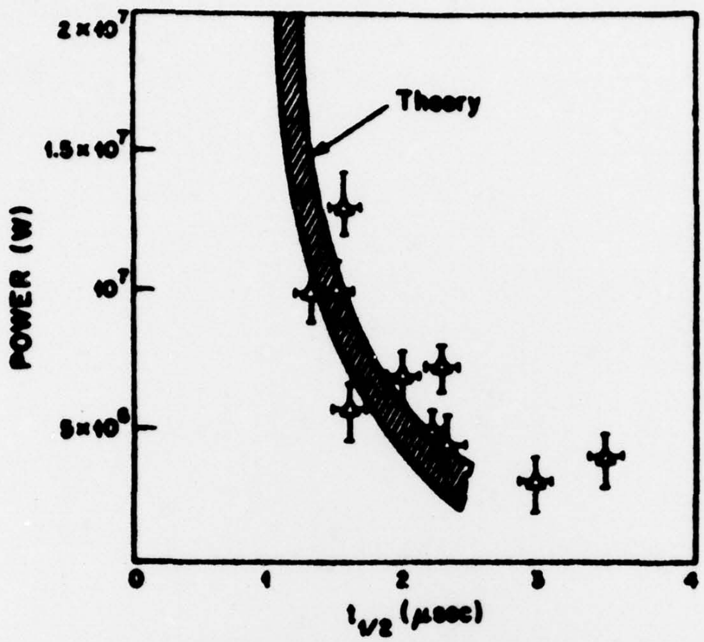


Figure 2. The time for the central aperture power to drop 50% has been plotted as a function of incident power. The cross-hatched area indicates the theoretical predictions for $0.8 \times 10^{-3} \leq \alpha \leq 2.4 \times 10^{-3}$ cm^{-1} and an aperture position uncertainty of $\pm$ 0.05 cm (Ref 4).

On the other hand, the plasma in single point air breakdown will spread 1 mm in 34 μs for intensities of 10^6 W/cm^2 and in 3.4 μs for 10^7 W/cm^2 (Figure 3). In the same time regime that the plasma is spreading, the intensity available to it is being reduced by the blooming. The threshold intensity for breakdown remains constant, so that a plasma is initiated prior to the blooming decay. As the plasma grows, however, the blooming reduces the flux available to it which results in a slower expansion velocity and concomitant lower absorption and reflection. Finally, the intensity is reduced below plasma maintenance with a cut-off time earlier than if the blooming were not present. One may therefore postulate cases where the total energy transmission with both effects present is greater than that with breakdown only, i.e., $E_{Bl + Br} \geq E_{Br}$ (Figure 4).

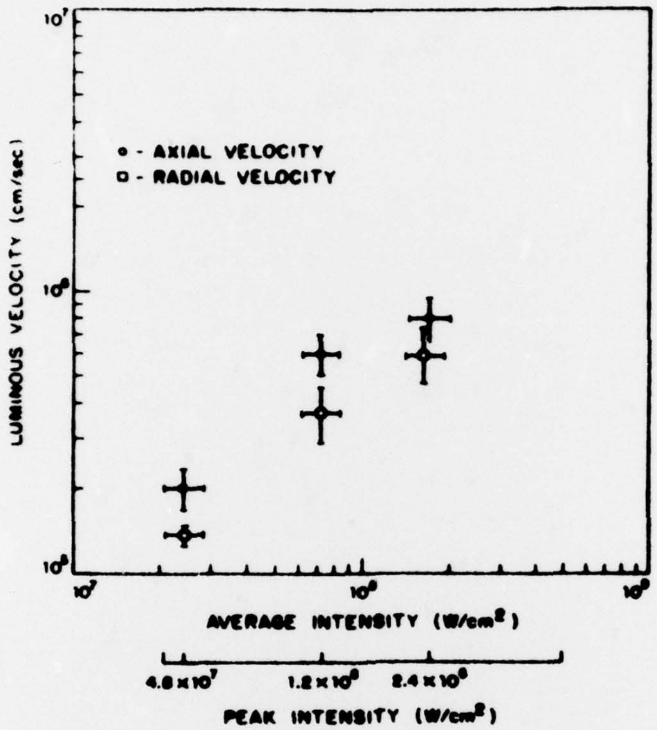


Figure 3. Axial and radial velocities of breakdown plasmas (Ref 3).

For the plasma spread, a simple model assumes a radial growth with a velocity $V_r = \alpha I^k$, where I_o is the beam intensity, and all the radiation is either absorbed or scattered. The transmitted energy for a rectangular pulse of time, t_p, and beam radius, R_o, will simply be

$$E_t = \int_o^{t_c} \left[I_o \pi R_o^2 - I_o \pi (\alpha I_o^k t)^2 \right] dt \tag{1}$$

where t_c is the time required for the plasma to fill the beam, i.e., $t_c = \frac{R_o}{\alpha I_o^k}$. Integrating, one gets

$$E_t = \frac{2R_o I_o^{-k} E_o}{3\alpha t_p} \quad t_c < t_p \tag{2}$$

$$E_t = E_o \left[1 - \frac{\alpha^2 I_o^{2k} t_p^2}{3R_o^2} \right] \quad t_c > t_p \tag{3}$$

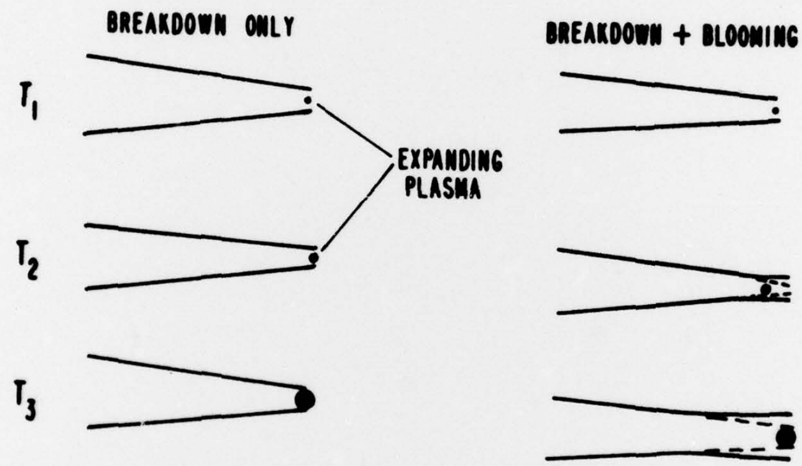


Figure 4. The concept of increased energy transmission due to the interaction of short time thermal blooming upon an air-breakdown induced absorbing plasma. The sequence of events is: (t_1), the plasma is initiated in both cases; (t_2) the plasma expands, but blooming also starts, lowering the available intensity and thus reducing the spreading velocity; (t_3) without blooming, the plasma fills the beam; with blooming, the plasma expansion is reduced and prematurely extinguished with higher total energy transmission.

This model will become increasingly complicated if one assumes that the initial intensity also varies with time due to the blooming. The intensity is then given by (5)

$$\frac{I(r,z,t)}{I_o} = 1 - \beta_o(z)\left[1 - \frac{3r^2}{a^2D(z)} + \frac{r^4}{a^4D^2(z)} \exp - \frac{r^2}{a^2D(z)}\right] \tag{4}$$

$$\beta_o(z) = \delta_o(z)(E/E_f)\ t^3/t_p t_f^{\ 2} \tag{5}$$

$$\delta_o(z) = \frac{16}{3} \cdot \frac{f^2}{k^4a^8} \int_o^z \frac{dz'}{D(z')} \int_o^z dz'' \frac{\exp(-\alpha z'')}{D(z'')^2} \tag{6}$$

$$\left[D(z')\right]^{\frac{1}{2}} = 1 - z/f + (z/ka^2) \tag{7}$$

$$t_f = f/kac \tag{8}$$

$$E_f = \pi c^2 / \left[\frac{3}{2} N(\gamma - 1)\ \alpha k^2\right] \tag{9}$$

where E is the total energy, a is the near field e^{-1} beam radius, c the speed of light, $k = 2\pi/\lambda$ where λ is the wavelength, z the path length, f the focus, γ the ratio of specific heats, α the absorption coefficient, and N the refractivity. I_o in Equation (1) is now replaced by Equation (4). Also, the limits of integration must reflect the fact that at some point the intensity will fall below plasma maintenance threshold. At that point, all plasma induced absorption ceases. The beam will propagate further until the plasma shadow is filled by diffraction and threshold is again reached. This process can be seen in the laboratory in the string of "plasma beads" along the propagation path near the focal volume. More generally, the thermal blooming effect is a volume effect, in which a statistical local plasma blackout is embedded. The problem of treating this combined process theoretically has not been solved.

3. Experimental Approach

Figure 5 schematically illustrates the experimental arrangement. A single shot Lumonics 602A CO_2 Transversely Excited Atmospheric (TEA) laser beam, 45 J energy output, with unstable resonator optics, is focussed through a 5.84 m blooming cell and breakdown is initiated outside the cell exit in the focal volume of the beam in laboratory air (dirty air case).

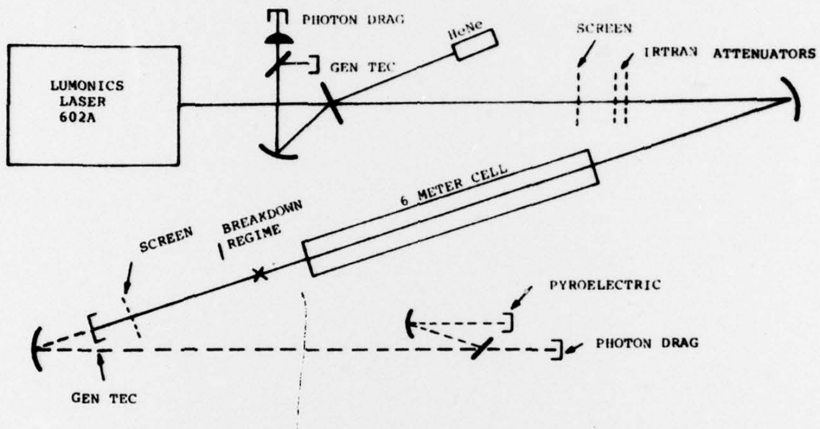


Figure 5. Experimental setup.

There is a need to spatially separate the two effects so that the breakdown with and without thermal blooming may be examined. Alternate experimental approaches, in which blooming and breakdown are spatially not separated, involve significantly more complexity and are in fact unworkable and non-simulating. If the focal volume occurs within the blooming cell, significant linear attenuation occurs in that volume as well. One cannot then separate the two effects of breakdown and blooming. Furthermore, by allowing the breakdown to occur outside the cell, the real atmospheric case is actually better simulated as little linear absorption will occur in the focal volume of a high energy laser beam.

The measurement procedure is as follows: First (A), an attenuating copper screen (9% transmission) and two 10 cm diameter Irtran flats are introduced in front of the cell to reduce the total energy below breakdown. Baseline measurements of the total energy are made with a Gen Tec meter, a photon drag detector (Rofin) is used for observing the on-axis temporal intensity behavior, and for obtaining a one-dimensional integrated energy profile, the focal point of the beam is imaged onto a Laser Precision 32-element pyroelectric array. Representative examples of each of these outputs are shown in Figures 6-8. Next (B), the screen is removed resulting in the breakdown only case. For (C), the Irtrans are removed, the screen replaced, and small amounts of propylene are added until the energy level is identical to that in case (A). Intensity and beam diameter will be the same, then, for breakdown at the cell exit. Finally (D), the screen is removed giving the breakdown and blooming case to be compared with the measurements of (B). It is interesting to note that the energy transmitted in the presence of breakdown is highly repeatable (5% excursions) when multiple breakdowns occurred. A randomness of a few breakdowns occurring in the presence of many will result in a small change in the overall transmission. However, when the intensity is borderline threshold, then large excursions (25-50%) will occur.

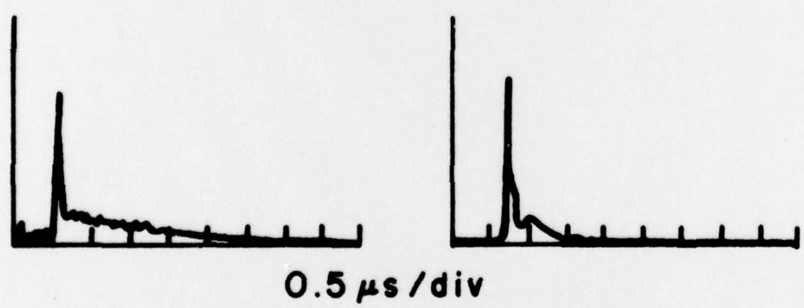


Figure 6. On-axis temporal intensity profile. Left, no blooming; right, blooming. Y scale; arbitrary units. Notice sharply cut-off tail due to blooming effect.

BREAKDOWN: NO BLOOMING

BREAKDOWN: BLOOMING

Figure 7. Integrated energy traces from Gen Tec detector. Each photo has 6 runs; upper traces (3 shots, 0.2 V/cm), transmission at reduced power; lower traces (3 shots, 0.5 V/cm), full power; right photo has traces superimposed showing increased energy (50%) over left photo.

4. Experimental Results

Figure 8 shows the beam profiles of the integrated intensity taken with the pyroelectric array with several shots averaged. The main features show that the beam with and without breakdown and no blooming averages to a similar profile. The blooming, however, results in increased energy in the side lobes of the beam, and a somewhat reduced peak. (In the Figure all curves were normalized to their respective peaks.)

Figure 9 gives the experimental results of the experiment. For the above data, the focal point of the beam was 1.956 meter from the cell exit. The breakdown length was approximately 4.26 m with no absorption and consisted of multiple plasmas. The breakdown data was surprisingly consistent as indicated in the curve. Quite often, one could not distinguish any transmitted energy differences over several separate runs. In all cases, however, the energy transmitted in the blooming case was higher than in the non-blooming cases.

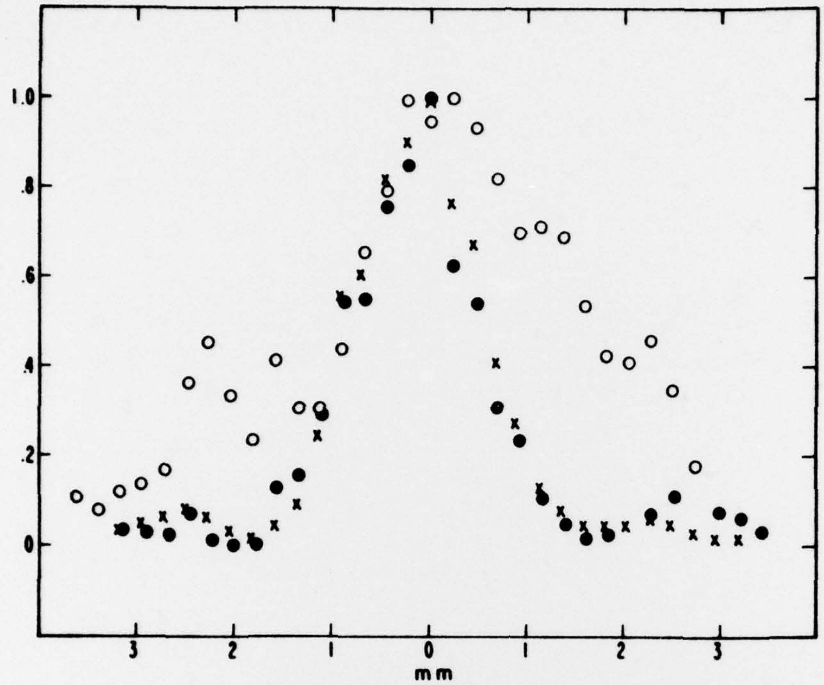


Figure 8. Integrated energy profiles. Each profile is the average of several shots. x - transmission; ● - breakdown-only; o - breakdown and blooming; all curves normalized to unity. Note that the breakdown-only case maintains the same basic profile, while the blooming causes spreading with resulting increased energy transmission.

5. Discussion and Application

As observed in Figure 9, the maximum energy transmitted was 50% higher in the blooming-breakdown case than in the breakdown-only case. This will, of course, be dependent on the beam cross section in the focal volume. A wider beam with commensurate energy increase to achieve identical peak flux intensity, would have higher transmission simply because the plasma would require a longer time to fill the cross section. Therefore, the beam spot size plays a significant role and higher levels of transmission than the 50% achieved in this particular example are expected.

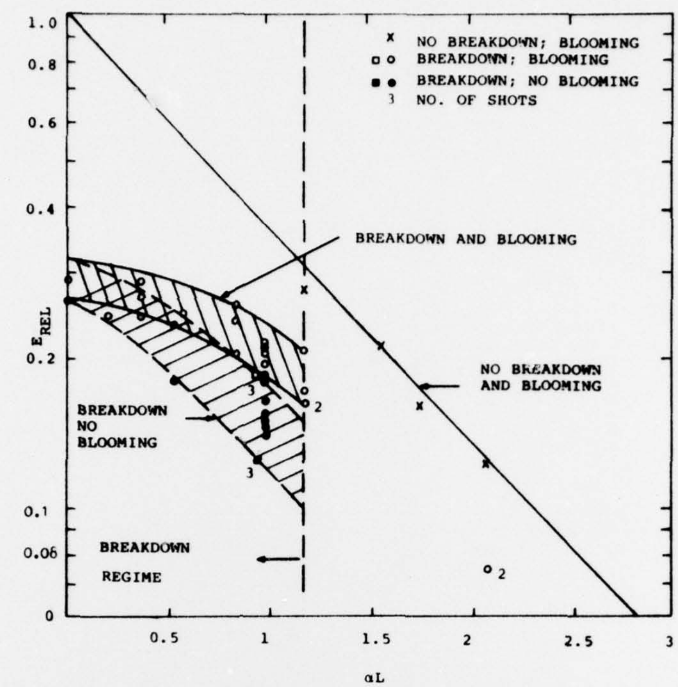


Figure 9. Experimental results: total energy versus the product of absorption coefficient versus path length. The breakdown regime is left of the dashed vertical line; the upper band of data has blooming present, the lower band does not, demonstrating the increased transmission effect.

How applicable will these results be for high energy laser systems? Efficient target interaction phenomena requires the ignition of a laser supported detonation (LSD) wave and the immediate reduction of the intensity to lower levels for enhanced coupling (6). The surface plasma ignition flux levels are roughly 10^7 W/cm^2 and plasma maintenance requires 0.5-8 x 10^6 W/cm^2. For representative short pulses (100-300 ns duration), air breakdown will occur at intensity levels of 10^8-10^9 W/cm^2 (7, 8). Therefore, the ideal pulse shape would be one with a spike of 10^7 W/cm^2 lasting 100-300 ns, followed by a tail of longer duration of 10^6 W/cm^2, thus avoiding air breakdown and allowing thermal blooming which will be partially correctable by adaptive optics.

However, if the beam is spatially inhomogeneous, i.e., hot spots as presently observed with present laser transmitters, then these significantly higher levels of intensity will result in air breakdown near the target. Reducing the average peak intensity to accomodate these peak variations is undesirable because of reduced target coupling. Therefore, the results of this study indicate that the combined effects of thermal blooming and breakdown must be included in detail in the modeling process if optimum energy transfer within operational constraints is to be realized. Preliminary estimates indicate that this optimum energy transfer depends critically on a judicious selection of the pulse structure.

6. Conclusions

An experiment has been performed combining the effects of short-time thermal blooming and air breakdown. The experiments demonstrate that, for the cases investigated, total energy transfer is higher for breakdown with blooming than without. Energy increases up to 50% have been experimentally observed. Breakdown processes are highly sensitive to the thermal blooming structure, and the combination of both effects must be taken into account if optimum energy delivery to the target is to be achieved.

References

1. D. C. Smith, Proc. IEEE 65, 1679 (1973).

2. D. E. Lencioni, Optics Research, Lincoln Laboratory, 1, 19 (1973),

3. D. E. Lencioni, L. C. Pertingill, Optics Research, Lincoln Laboratory, 2, 27 (1973).

4. R. W. O'Neill, H. Kleiman, J. F. Lowder, Appl. Phys. Lett., 24, 118 (1974).

5. A. H. Artken, J. N. Hayes, P. B. Ulrich, Appl. Optics, 12, 193 (1973).

6. R. W. Sepucha, AHELSPO, Huntsville, Alabama, private communication.

7. D. C. Smith, J. of Appl. Phys., 48, 2217 (1977).

8. J. Reilly, P. Singh, G. Weyl, AIAA Fluid and Plasma Dynamics Conference, June 27-29, 1977.