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TITLE **KINETIC AND FLUID SIMULATIONS OF AIL BREAKDOWN**

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TIME-DEPENDENT FLUID MODEL

The mean properties of the breakdown plasma produced during high-power microwave propagation through an experimental chamber filled with air at fixed pressure were investigated by means of a time-dependent fluid model. The latter is derived from the Boltzmann equation assuming a shifted Maxwellian for the electron velocity distribution function; namely,

$$f(n, \underline{v}_0, T) = n \,(m / 2\pi kT)^{3/2} \exp(-m(\underline{v} - \underline{v}_0)^2 / 2kT) \qquad (1)$$

where n is the density, $\underline{v}_0$ is the mean velocity induced by the microwave field and T is the temperature. Appropriate moments of the Boltzmann equation are performed to obtain equations for particle, momentum and energy conservation. In each case, the collision integrals which incorporate elastic, inelastic and ionization processes through energy dependent cross-sections reduce to rate coefficients. Neglecting electron spatial diffusion and ponderomotive effects, the resulting equations can be written:

$$\partial n / \partial t = \nu_i(v_0, T)\, n \qquad (2a)$$

$$\partial \underline{v}_0 / \partial t = -e\underline{E}/m - (\nu_m(v_0, T) + \nu_i(v_0, T))\, \underline{v}_0 \qquad (2b)$$

$$\partial T / \partial t = -(2\nu_e(v_0, T)/3 + \nu_i(v_0, T))\, T \qquad (2c)$$

where ν_i is the ionization rate, ν_m is the momentum exchange rate and ν_e is the energy exchange rate. These equations advance the local fluid parameters in time with $\underline{E}$ being determined from Maxwell's equations.

Kinetic Treatment

In our kinetic treatment, the electron distribution function is expanded in terms of Legendre polynomials ($P_l^0(\mu)$) in the frame of reference moving with the average velocity of the electrons with the expansion carried out to four terms i.e.,

$$f(V,\mu) = \Sigma_l f^{(l)}(V) P_l^0(\mu) \qquad (3)$$

where $V(= |\underline{v} - \underline{v}_0|)$ is the electron speed and μ the cosine of the angle between the electric field and the velocity vector, both measured in the drift frame of the electrons. Substituting equation (5) into the Boltzmann equation and dotting the result with the first four Legendre polynomials yields a set of coupled equations for the $f^{(l)}$, l=0-3, given by:

$$df^{(l)}/dt-(eE/m_e+dv_0/dt)[(l/(2l-1))(d/dV-(l-1)/V)f^{(l-1)}+((l+1)/(2l+3))$$

$$(d/dV+(l+2)/V)f^{(l+1)}] = (l+1/2) \int d\mu\, P_l^0(\mu)\, (S_{in}-S_{out}) \qquad (4)$$

with

$$dv_0/dt = -eE/m_e + \int d\mu \int dV\, V^3 \mu\, (S_{in}-S_{out}) / n_e \qquad (5)$$

where $S_{in} - S_{out}$ represents the Boltzmann collision integral which includes elastic, inelastic and ionization terms. A full microscopic treatment of elastic and inelastic processes appropriate to electron-air interactions is included in our analysis and the cross-sections of Phelps [1], [2] are used in both fluid and kinetic treatments.

WAVE PROPAGATION AND ATTENUATION

The 1-D wave equation which describes field propagation through the fluid is derived so as to include field reflection and focusing. Introducing an area factor that changes along the path of propagation and making use of Poynting's theorem results in:

$$\varepsilon\, \partial^2 E / \partial t^2 - c^2(\partial^2 E / \partial z^2 + A^{-1}(\partial A / \partial z)(\partial E/\partial z)) = -4\pi\, \partial J / \partial t \quad (3)$$

where z is the direction of propagation, ε is the dielectric constant, A is the area of the microwave beam and $J = env_0$ is the current density. The terms from left to right provide the effects of reflection, propagation, focusing and fluid coupling, respectively. The fields are advanced in time and space with the current density being determined from the fluid equations.

Where experimental conditions require distinction between propagation directions the equation is modified by the introduction of $L = E_x + B_y$ and $R = E_x - B_y$; i.e., the left and right propagating components of the wave field. Substituting L and R into Maxwell's equations leads to the following coupled wave equations for left and right propagation:

$$(2\varepsilon/(\varepsilon+1))(1/c)\, \partial L / \partial t = \partial L / \partial z + ((\varepsilon-1)/(\varepsilon+1))\, \partial R / \partial z +$$

$$(1/2A_L)(\partial A_L/\partial z)[L+((\varepsilon-1)/(\varepsilon+1))R]-8\pi j/c(\varepsilon+1) \quad (4a)$$

$$(2\varepsilon/(\varepsilon+1))(1/c)\, \partial R / \partial t = - \partial R / \partial z - ((\varepsilon-1)/(\varepsilon+1))\, \partial L / \partial z -$$

$$(1/2A_R)(\partial A_R/\partial z)[R+((\varepsilon-1)/(\varepsilon+1))L]-8\pi j/c(\varepsilon+1) \quad (4b)$$

$$E=(R+ L) / 2 \quad (4c)$$

where A_R and A_L are the area factors for the right and left propagating waves, respectively.

EXPERIMENTAL GEOMETRY

A two dimensional sketch of the experimental geometry (discussed in (1)) is presented in the top half of the Figure on the right. The incident microwave pulse propagates from left to right and is focused onto a copper screen placed at 45^0 to the Poynting vector. The reflected pulse propagates at 90^0 relative to the incident direction and interferes with the incident pulse (thereby mimicking the interference of two intersecting beams), producing regions of constructive interference that are above the threshold for breakdown. The power profile of the reflected pulse is drawn in to illustrate the fall-off of power along the simulation line.

The 1-D geometry chosen to simulate this experiment is shown in the bottom half of the figure to the right. A grid four wavelengths (λ = 10.5 cm) in size is chosen with a transmitting boundary on the left side and a reflecting boundary placed inside the cell. The incident microwave pulse enters the transmitting boundary on the left, propagates to the right and is focused on the reflecting plate according to the area factor A_R. The reflected wave propagates to the left, is defocused according to an area factor A_L and exits through the transmitting boundary. A_R is obtained from measurements taken along the propagation path (with the reflecting surface removed) of the focused power of a reference cw, low-power source. Similarly, A_L is derived from measurements of the beam profile taken perpendicular to the direction of propagation. Note that the time for the reflected pulse to reach a particular point in the simulation cell is the same as that for the reflected pulse in the experiment (off a 45^0 surface) to reach the simulation line. Note also that the corresponding power at the simulation point is given by the beam profile.

OPTICAL EMISSIONS

The coronal approximation (collisional excitation followed by radiative decay) with quenching in conjunction with a three level atom (sketched in the right-hand figure) are used to obtain the volume emissivity of the breakdown plasma in the N_2 3371 A and N_2^+ 3914 A lines. The emissivity can be written,

$$\varepsilon_\nu \,(\mathrm{ergs / cm^3\, s\, ster}) = (h\nu / 4\pi)\; n_3 A_{32} \qquad (5)$$

where ν is the line frequency, A_{32} is the Einstein spontaneous transition rate and n_3 is the population density of the upper state. The latter is calculated from the rate equation given by,

$$\partial n_3 / \partial t = n_1 C_{13} - n_3 A_{32} - n_3 Q \qquad (6)$$

where n_1 is the ground state population, Q is the quenching rate and C_{13} is the collisional excitation rate derived by folding the electron velocity distribution function against the cross-sections shown on the right. Equations (5) and (6) are solved in conjunction with the fluid and Maxwell's equations and the results compared with high speed (300 ps resolution) photometer measurements of 3371 and 3914 line intensities and CCD time-integrated measurements of emission scale lengths (see (1)).

EXPERIMENTAL RESULTS

The relevant experimental data for comparison with theory is summarized in the figure on the right. A plot of peak power density measured at the focal plane vs. time for the incident (dark trace) and transmitted (light dotted trace) microwave pulses is shown at the top of the figure. These measurements are known to approximately ± 30 % and zero time is chosen to correspond to a particular power level. Note that severe attenuation as seen in the transmitted pulse appears at around 120 ns into the incident pulse. This coincides with the formation of a breakdown layer at a quarter wavelength (λ = 10.5 cm) from the reflecting surface. In addition an extended tail from 150 ns to 250 ns can be seen in the transmitted pulse.

The interferometry data is summarized in the middle entry of the figure. Shown is a plot of the normalized, transmitted X-band (9.7 GHz) signal (dark trace) and the beat between that same signal and a reference signal (light dotted trace) vs. time. Note that attenuation of the X-band signal occurs about 10 ns later than that of the S-band microwave pulse. This data gives direct information on the density and collisionality of the breakdown plasma. Preliminary results indicate a peak electron density of 2.6×10^{11} cm^{-3} at 120 ns with an ionization rate of approximately $\nu_i = 1.3 \times 10^8$ s^{-1}. The momentum exchange rate derived from absorption of the X-band signal is $\nu_m = 3.3 \times 10^{10}$.

High speed (300 ps resolution) photometer measurements of emission in the N_2 3371 A (dark trace) and N_2^+ 3914 A (light dotted trace) lines are plotted in the bottom panel as a function of time. On a normalized scale the 3914 A line preceeds 3371 A by about 23 ns while the 3371 A emission extends out to longer times. In absolute magnitude the 3914 A line intensity is a factor of 4 to 5 less than 3371 A. The relative amplitude and time of these lines carries information about the electron temperature as described in a recent presentation.

SIMULATION RESULTS

Three simulations at pressures of 1, 0.1 and 0.03 Torr were run to compare with experimental data. Detailed results from only the 1 Torr calculations are shown at the right. The input electric field at the focal plane (z = 0. 0 m in our cell) is shown in the experimental data above. The figure on the right shows the time history of the microwave pulse at a quarter wavelength from the reflecting surface (z = 0.3⁄ m in our cell). The latter corresponds directly to the transmitted pulse in the experiment. Note that severe attenuation occurs at approximately 120 ns into the pulse. This is to be compared to the value of 120 ns measured in the experiments. An additional feature is the existence of a significant tail on the transmitted pulse, in qualitative agreement with the data.

Plots of electron density, mean kinetic energy and thermal energy vs. time are also shown to the right. The calculated ionization and momentum exchange rates are $\nu_i = 2.9 \times 10^8\ s^{-1}$ and $\nu_m = 1.0 \times 10^{10}\ s^{-1}$, respectively.

Plots of the volume emissivity in the N_2 3371 A and N_2^+ 3914 A lines vs time are shown in the figure on the right. Note that the normalized peak of 3914 preceeds that of 3371 by about 35 ns, compared with the measured value of 23 ns. In absolute magnitude the 3914 A emissivity is calculated to be about a factor of 167 less than that of 3371 A. No comparable measurement exists.

	Experiment	Theory
I. 1.0 Torr		
Peak Power (MW / m^2)	6.20	5.21
t_{peak} (3914, ns)	152	150
t_{peak} (3371, ns)	175	185
ν_i (cm^3 / s)	$1.3x10^8$	$2.9x10^8$
ν_m (cm^3 / s)	$3.3x10^{10}$	$1.0x10^{10}$
t_{bd} (ns)	120	120

	Experiment	Theory
II. 0.1 Torr		
Peak Power (MW / m^2)	53.9	21.6
t_{peak} (3914, ns)	200	190
t_{peak} (3371, ns)	230	208
v_i (cm^3 / s)	-----	2.9×10^8
v_m (cm^3 / s)	-----	1.0×10^{10}
t_{bd} (ns)	160	160

KINETIC EFFECTS

Detailed solutions of the Boltzmann equation for air breakdown yield highly non-Maxwellian distribution functions. The net effect on the ionization rate and on the excitation rates for λ3371 and λ3914 are shown in the figures on the right. For energies less than 10 ev the ionization rate is higher for kinetic calculations due to the presence of a high-energy tail while for greater energies the ionization rate is less due to runaway depletion of the tail of the distribution function. A similar result is obtained for the excitation rates. The fact that input power levels for the fluid sumulations at 1 Torr and 0.1 Torr had to be reduced by 20% and a factor of 2.5 respectively to yield agreement with the measured breakdown time is evidence for these effects. The slower decay of the transmitted pulse at 0.03 Torr than predicted by fluid simulation is also indicative of these kinetic effects. To the extent that the excitation ratios shown in the bottom figure are indicative of the relative line ratios, kinetic theory would predict a lower ratio below 20 ev and a higher one above 20 ev than fluid theory.

SUMMARY

Analysis and interpretation of the experimental data is still in progress. In particular, the interferometer measurements obtained by SRI (Stadler and Eckstrom) are being repeated to confirm or resolve large, unexpected discrepancies between inferred collision rates and calculated rates. In addition, the photometer measurements obtained with estimated calibration curves yield line ratios significantly different from theory. These measurements will also be repeated. Thus the only quantitative comparisons available at present between theory and experiment are the time to breakdown (indication of ionization rate), the transmitted pulse, and the time history of λ3371 and λ3914 emissions. The pulse power levels used in the fluid simulations were adjusted to yield agreement on the time to breakdown. At 1 and .03 Torr the adjustment was well within experimental accuracy (power was reduced by 20% at 1 Torr and no adjustment at 3 Torr). At 0.1 Torr the power needed to be reduced by a factor of 2.5 in order to yield an accurate breakdown time. This discrepancy, however, can be explained in terms of kinetic effects (see below). The transmitted pulse shapes decay at a rate faster than predicted at 1.0 and 0.1 Torr, suggesting that the collisionality of the plasma is higher than predicted -- perhaps due to the existence of anomalous wave particle interactions. The decay at .03 Torr is less than predicted by fluid theory, a result that could be explained by kinetic effects (see below).

The λ3914 and λ3371 light emission pulses are in good agreement with the simulations in terms of the rise in intensity, the time of the peak intensity, and the decay of the pulse(maximum discrepancies of 30-50%). In both experiment and theory the decay for λ3914 is consistent with quenching and spontaneous decay rates. For λ3371 the decay rate is less than expected and suggests the existence of additional heating or enhanced excitation.