Thermal stability of a plasma in a homogeneous microwave field in Air

J. Rasch[1], D. Anderson[1], M. Lisak[1], V. E. Semenov[2], J. Puech[3]

[1] *Chalmers University of Technology, Göteborg, Sweden*

[2] *Institute of Applied Physics, Nizhny Novgorod, Russia*

[3] *Centre National d Études Spatiales, Toulose Cedex 9, France*

Abstract

When microwave gas breakdown occurs in inhomogeneous fields, the initial breakdown volume might be very small, and not necessarily immediately harmful to the microwave system. It is therefore necessary to look at the more long term evolution of this localized breakdown plasma. We analyze a spherical region of plasma in a homogeneous electric field under the breakdown threshold. We assume atmospheric pressures and use the quasistatic approximation, and find that the plasma sphere is thermodynamically unstable. If the initial plasma is smaller than a critical radius it dissappears, whereas if it is larger, it will expand indefinitely.

Introduction

Microwave breakdown in a gas entails the avalanche production of free electrons in the microwave system, resulting in a breakdown plasma that might cause serious damage and disturbances to the system [1, 2, 3]. The breakdown threshold is the point of balance between ionizing mechanisms and electron loss mechanisms, above which breakdown becomes a risk. The most important factor for determining the threshold is the electric field strength, which is the agent giving sufficient energy to the electrons for them to make ionizing collisions with neutral gas molecules. To determine the breakdown threshold we use the continuity equation

$$\frac{\partial N}{\partial t} = \nabla^2(DN) + N(\nu_i - \nu_a) - \alpha_r N^2 \qquad (1)$$

where N is electron density, D the diffusion coefficient, ν_i the ionization frequency, ν_a the attachment frequency, and α_r the recombination coefficient. The breakdown threshold in CW conditions is defined as the point when $\partial N/\partial t = 0$. Since ν_i depends heavily on the electric field strength, in inhomogeneous fields the immediate breakdown volume might be very small, and the immediate harmful effects will be very limited [4], [5]. In this situation it is important to determine the subsequent evolution of the breakdown plasma to assess the risk to the system. Will the plasma grow to fill the system, or will it be contained indefinitely? It is well known from experiments that plasma can form in fields which are below the breakdown threshold if there exists small regions of enhanced field or local sources of strong heating. These small regions are known to be able to expand rapidly, where the expansion speed depends on the energy density in the microwave field [6], [7]. There are many physical mechanisms which may be important in such situations, but at atmospheric pressures when the breakdown plasma is very small, the are only a few. The immediate saturation mechanism which halts the exponential growth of the breakdown plasma is the suppression of the internal electric field, due to the polarizing action of the free electrons. On longer time-scales other effects become important, mainly the Joule heating of the plasma, and subsequently the heating of the surrounding air. This will lower the surrounding breakdown threshold, making it possible for the plasma volume to expand. Inside the plasma the temperature will rise, decreasing the gas density, increasing the electron density, which lowers the internal field. These three effects combine to produce a net heating which varies roughly inversely to the temperature of the plasma. This implies the possibility of a stationary state of plasma region. However, a closer examination will show that the heat transport and generation mechanisms causes the stationary plasma region to be unstable.

Effects of temperature and electron density

At atmospheric pressures we can usually neglect diffusion ($L_a \equiv \sqrt{D_a/\nu_a} \ll L_{plasma}$), and the plasma density saturates before recombination becomes important, which implies a breakdown threshold determined by the equality of the ionization and attachment frequencies.

$$\nu_i \approx \nu_a \tag{2}$$

For high constant pressures, these frequencies are equal at a field strength E_a, which depends on temperature as

$$E_a \approx E_{a0}\frac{T_0}{T} \tag{3}$$

where E_{a0} is the breakdown field at room temperature, T_0. Thusm the breakdown threshold will locally depend on temperature, and a breakdown plasma will be formed locally when $E_{local} > E_a$. This means that in a homogeneous field, E_0, plasma will form locally at a spot heated to $T_1 = T_0E_{a0}/E_0$, and the outer rim of the plasma volume will have the temperature T_1.

Inside the plasma the electrons will oscillate in response to the electric field and cause a net polarization, $\mathbf{P}$, acting to suppress the internal field

$$\mathbf{P} = \frac{e^2N}{m(\omega^2+\nu_c^2)}(1+i\frac{\nu_c}{\omega})\mathbf{E}_{plasma} \tag{4}$$

where e is the electron charge, m the electron mass, ν_c the effective electron-neutral collision frequency for momentum transfer, and ω the field frequency. The field in the plasma is $\mathbf{E}_{plasma} = \mathbf{E}_0 - \mathbf{P}/\varepsilon_0$. Under the quasistatic approximation ($L_{plasma} \ll \lambda_{field}$), the field strength inside a spherical plasma in a homogeneous electric field is

$$E_{plasma} = \frac{3E_0}{\sqrt{(3-n)^2 + (n\frac{\nu_c}{\omega})^2}} \tag{5}$$

The electron density in the plasma will grow until the field is suppressed to the breakdown threshold $E_{plasma} = E_a$.

Thermal balance

The breakdown plasma undergoes Joule heating, described by

$$q_{plasma} = < \frac{\partial \mathbf{P}}{\partial t} \cdot \mathbf{E}_{plasma} > \approx 3\varepsilon_0 \omega E_0^2 \frac{T_1}{T} \sqrt{1 - (\frac{T_1}{T})^2} \tag{6}$$

The remaining problem is that of thermal balance, described by the heat conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\kappa(T)\nabla T) + q_{plasma}(T) \tag{7}$$

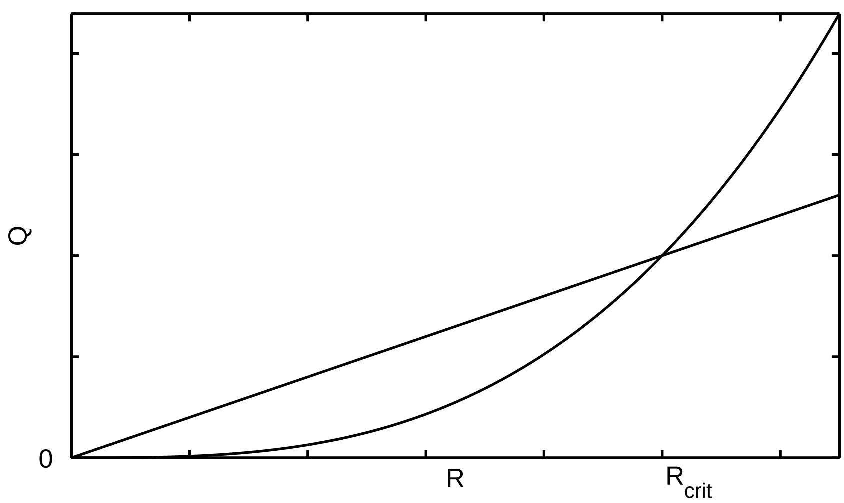
where ρ is the density, c_p the heat capacity at constant pressure, and $\kappa(T)$ is the thermal conductivity. Integration over the plasma volume, $4\pi R^3/3$, yields

$$4\pi \int_0^R \rho c_p \frac{\partial T}{\partial r} r^2 dr = 4\pi R^2 \kappa(T_1) \frac{\partial T}{\partial r} + 4\pi \int_0^R q r^2 dr \equiv -Q_{loss} + Q_{Joule} \tag{8}$$

Thermal equilibrium is reached at $Q_{loss} = Q_{Joule}$. In a limited range of temperatures the thermal conductivity of Air can be approximated as $\kappa(T) \approx \kappa_0 (T/T_0)^{3/4}$, and the solution of the thermal profile outside the sphere is easily obtained. This makes it possible to approximate the two thermal terms as

$$Q_{loss} \approx \frac{16\pi}{7} \kappa_0 (\frac{T_1}{T_0})^{3/4} (T_0 (\frac{T_0}{T_1})^{3/4} - T_1) R \qquad Q_{Joule} \approx 2\pi \varepsilon_0 \omega E_0^2 R^3 \tag{9}$$

The variation of these terms with R, as seen in the figure below, has a direct physical implication.



There are two points of equilibrium, $R = 0$ and $R = R_{crit}$, where however only the zero solution is stable. This means that a plasma sphere in a homogeneous field will either contract to zero radius or expand indefinitely depending on whether the original radius is larger than R_{crit} or not.

Conclusions

We have investigated the thermal stability of a microwave breakdown plasma generated by local heating of Air. Under the assumptions of the model ($L_a \ll L_{plasma} \ll \lambda_{field}$) we can show that there exists a critical radius, below which the plasma will decay, and above which the plasma will expand indefinitely. The results of this study are of immediate importance in estimating the safe size for heated regions, and regions of enhanced field, in RF systems. In addition to this, the analysis clarifies the most important physical mechanisms in possible transistions from highly localized breakdown regions into large scale breakdown.

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