Imaging of Atmospheric Air Breakdown Caused by a High-Power 110-GHz Pulsed Gaussian Beam

Yoshiteru Hidaka, E. M. Choi, I. Mastovsky, M. A. Shapiro, *Member, IEEE*, J. R. Sirigiri, *Member, IEEE*, and R. J. Temkin, *Fellow, IEEE*

***Abstract*—We present the images of regular filamentary plasma arrays produced upon the breakdown of air at atmospheric pressure at the focal region of a high-power 110-GHz pulsed Gaussian beam. The source of the millimeter wave beam is a gyrotron that can generate up to 1.5-MW output power with 3-μs pulselength. This unique plasma structure exists only at high pressures. With decreasing pressure, the structure changes into layers of curved plasma sheets and into more familiar diffuse plasma. A main cause of the formation of the regular array structure appears to be the reflection from filaments. The successive generation of conductive filaments modifies the incident field pattern and creates local hot spots upstream of the existing filaments with regular spacing of roughly a quarter wavelength.**

***Index Terms*—Air breakdown, gyrotrons, plasma generation.**

I. Main Body

VOLUME air breakdown in wide ranges of pressures and frequencies has been extensively studied [1], [2]. Yet, very few breakdown experiments in the millimeter wave regime have been conducted [3], [4]. As the output power from millimeter wave sources such as gyrotrons increases, the breakdown of air becomes a critical issue in transporting the output radiation. It is our motivation to understand the breakdown physics in this frequency regime and discover differences, if any, from the previously well-investigated microwave breakdown results [5], [6].

Our experimental setup consists of a gyrotron and a focusing lens. The gyrotron, operating at 96-kV beam voltage and 40-A beam current, can generate a 3-μs-pulsed 110-GHz linearly polarized Gaussian beam with a maximum output power of 1.5 MW [7]. The lens compresses the beam radius down to roughly 4 mm at the waist, where the ambient air frequently breaks down with a field strength of above 4.4 MV/m (or 2.5 MW/cm^2 in intensity). The plasma images are recorded by a digital camera with its sensor exposed during the entire pulselength. Other diagnostics include transmitted power measurements with a diode detector and optical emission measurements with fast photodiodes.

We have found that the plasma generated by this beam at atmospheric pressure is a regular array of filaments elongated along the electric field polarization, as shown in Fig. 1. Fig. 1(a) shows the image of the array captured in the E-plane view, which illustrates the multiple plasma columns. The image shown in Fig. 1(b) reveals that these filaments are regularly arranged in the H-plane. The average axial distance between adjacent filaments on the beam axis is about 0.76 mm, which is slightly larger than a quarter wavelength ($\lambda/4 = 0.68$ mm) at 110 GHz.

We have conducted breakdown experiments with air at lower pressures in a chamber as well. The focused beam radius in this setup is also $\sim$4 mm. As shown in Fig. 1(c), as the pressure is reduced from 760 torr, the filaments are no longer well isolated in the transverse direction, i.e., the plasma tends to form sheets. Further reduction in pressure results in a diffuse plasma, as shown in Fig. 1(d). Breakdown cannot be achieved below 0.7 torr.

From the photodiode measurements, we have determined that the breakdown region propagates toward the radiation source. This backward propagation is believed to be caused by microwave power reflected from the breakdown region. Diode measurements verify the existence of reflected power, but the diffuse nature of the reflection makes quantitative measurements difficult. The power reflected from the thin filaments is strongly diffracted. This diffraction, in turn, leads to the observed array structure, as shown with the following HFSS model [8]. We assume that the initial filament forms at the focal point and model the filament as a perfectly conducting post. The resulting total E-field profile along with the post (white circle) is shown in Fig. 2(a). The field maximum occurs at about $\lambda/4$ upstream of the post. In the next stage, as shown in Fig. 2(b), we assume that the second filament forms at this hot spot. Likewise, a new maximum occurs at $\sim\lambda/4$ upstream of the second post, where the third post is assumed to form, as shown in Fig. 2(c). Fig. 2(c) clearly shows an excellent agreement of the curved crescent-like plasma structures between the simulation and actual experimental images, as shown in Fig. 2(d).

The diffuse plasma observed at low pressure is similar to the plasma seen in microwave breakdown experiments at conventional microwave frequencies. The new effect observed here is the formation of very intense reflecting filaments in breakdown at high pressure with high-frequency microwaves. The filaments are much thinner than a wavelength, and they are aligned along the electric field. We do not have a detailed explanation of this effect at this time. However, once a single filament is formed, we can explain the appearance of new filaments upstream of the original filament and the formation of an array, using the equivalent HFSS model of the reflecting posts presented in this paper. We hope to develop a detailed model of the pressure dependence of breakdown formation in

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The authors are with the Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: yhidaka@mit.edu).

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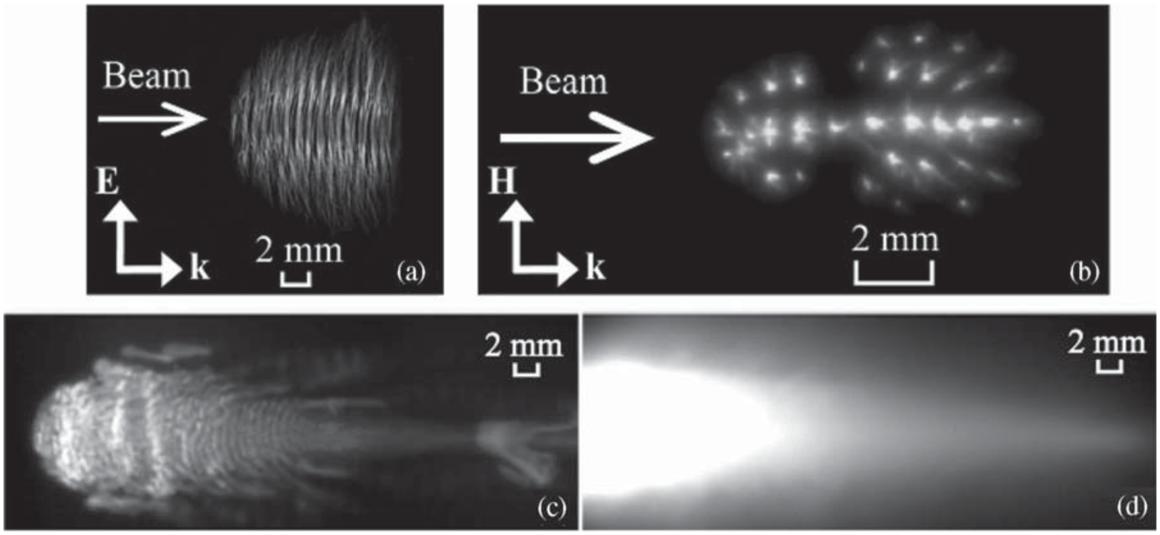

Fig. 1. Time-integrated images of air plasma in (a) E-plane at 760 torr and (b)–(d) H-plane at 760, 50, and 0.7 torr, respectively. The camera sensor is exposed during the entire microwave pulselength. Camera sensor gain settings are different in each shot. The light emission intensity decreases as pressure decreases.

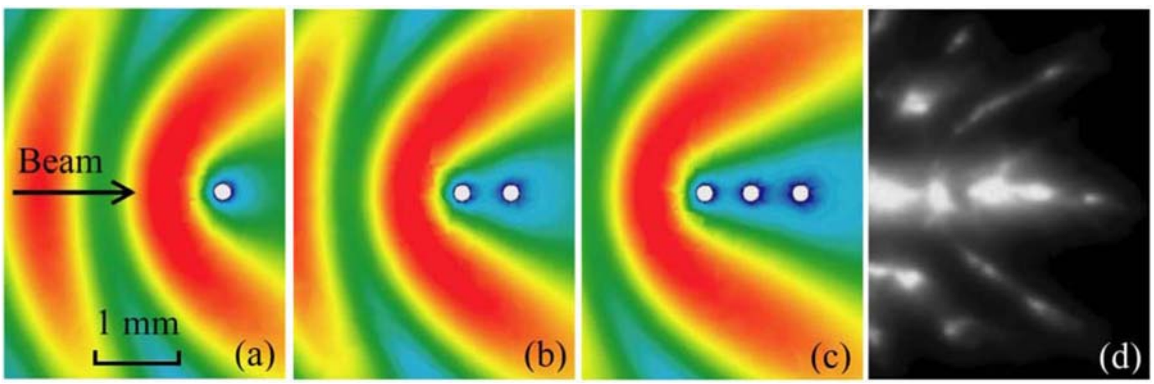

Fig. 2. Simulation results of total E-field magnitude with (a) one, (b) two, and (c) three plasma filaments modeled as (white circles) perfectly conducting metal posts. (d) Volume breakdown image at atmospheric pressure in H-plane.

a future paper. The variation of collisionality with pressure is likely to play a major role in such a model.

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