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RF BREAKDOWN IN A GAS-FILLED TE_{01} CAVITY*

Faya Wang#, Chris Adolphsen and Christopher Nantista
SLAC National Accelerator Laboratory, Menlo Park, CA 94025 USA

Abstract

An L-band (1.3 GHz) TE_{01} mode pillbox cavity has been designed to study rf breakdown in gas. Since there are no surface electric fields, effects from the electron interaction with the surface should not be present as in the DC breakdown case. A CCD camera was used to measure the integrated light pattern through holes in the cavity, and an ultrafast diode was used to observed the evolution of the plasma during breakdown. Some preliminary results of the tests are presented in this paper.

INTRODUCTION

For a self-sustaining gas discharge between two electrodes, there is a well-known breakdown criterion [1],

$$\gamma(e^{\alpha d}-1)=1, \quad (1)$$

where α and γ are the first and second Townsend coefficients. As γ depends on not only the gas type but electrode material, it is difficult to explore the breakdown characteristics of just the gas in a DC system. At SLAC, an L-band TE_{01}-mode pillbox cavity was designed with an iris plate perforated to pass light. This cylindrical "colander" cavity, illustrated in Fig. 1a, was fabricated in aluminium. Since there is no surface electric field and the peak electric field in the cavity forms a ring at roughly mid-radius, it should reveal the gas breakdown characteristics only. Three rings of holes were made in the iris of the cavity to allow imaging of the light emitted during and after breakdown from the plasma generated.

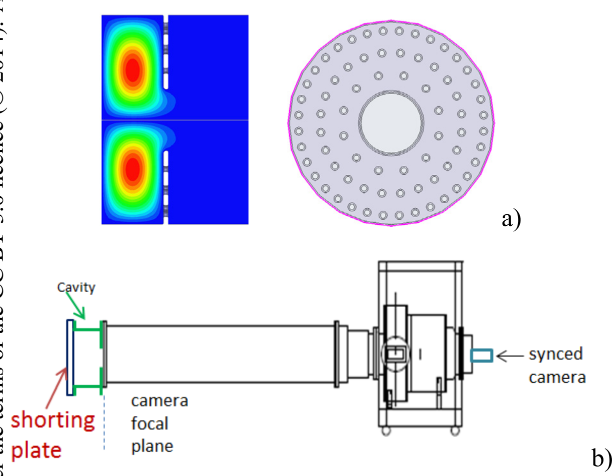

Figure 1: a) Cross-sectional side-view of RF electric field pattern in the circular TE_{01} cavity and the iris face hole pattern. b) The high power test setup.

The cavity was attached to the end of a 2.5 m long, 0.48 m diameter cylindrical waveguide, which is directly powered by a 10 MW L-band klystron through a TE_{01} mode launcher [2]. The high power test setup for the cavity is shown in Fig. 1b, and uses equipment from ILC waveguide component R&D [3-5]. Cold tests showed the cavity to be nearly critically coupled (β = 1.1) with an unloaded quality factor Q_0 = 32,700. With 1 MW of input power, the excited peak field in the cavity is 12.1 MV/m in steady state.

HIGH POWER TEST RESULTS

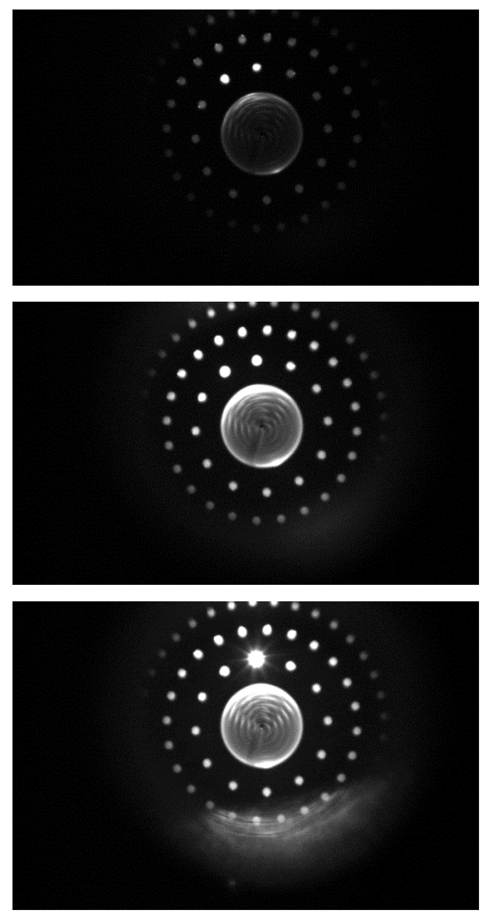

Figure 2: Typical images of rf breakdown with 25 μs long pulses.

We first ran the cavity filled with N_2 at 2 atm (absolute). A 25 μs RF pulse was used, which is short compared to the 1.6 ms klystron pulse capability. Figure 2 shows a few images of the integrated light emitted during RF breakdown events, where the RF was shut off a few

*Work supported by the U.S. Department of Energy Early Career Research Program under Project code LAB 11-572
fywang@slac.stanford.edu

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microseconds after the breakdowns occurred. As the surface of the cavity is a good reflector of light, it is difficult to discern from the image whether there is a plasma ring centered on the peak electric field.

We then replaced the camera with a fast photo-diode to measure the temporal characteristics of the light. The signal waveforms for a typical breakdown pulse are shown in Fig. 3. In this case, the input RF was left on for a longer period after breakdown. The initial slope of the input RF waveform is due to a modulator effect, and the step just after the breakdown is from cross talk between the input and reflected signals. After breakdown, the RF power continues to be reflected as it takes a long time for the plasma density to reduce to a level where the cavity is no longer detuned. That is, even though the light signal appears to go to zero, it is still finite and could be seen with a larger dynamic range detector.

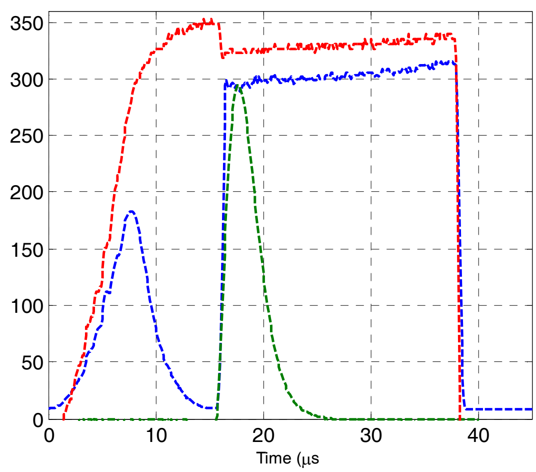

Figure 3: Typical breakdown waveforms, where the dashed red, blue and green lines are respectively, the input rf, reflected rf and photo-diode signal in arbitrary units.

In past studies of rf breakdown in gas [5], we have modelled (1D) the plasma density evolution using the continuity equation,

$$\frac{dn}{dt} = \alpha_i n - \gamma n - \alpha_r n^2, \tag{2}$$

with $\alpha_i = 8.8e^{-275P/E} P\mu E,$ (3)

$\alpha_r = 2.0 \times 10^{-6}(300/T_e)^{0.5}$[6], (4)

and $\gamma \approx 0.0073/P,$ (5)

where α_i is the ionization rate, γ the diffusion loss, α_r the recombination rate, μ the electron mobility, P the gas absolute pressure in Torr, E the electric field in V/cm, and T_e the time dependent plasma electron temperature in eV. Maxwell's equations in this situation give:

$$\frac{\partial D}{\partial t} + J_c = \nabla \times H = J_T, \tag{6}$$

where J_c is the conductor current of the plasma and J_T the electron current flow out of the plasma. With the combination of Eqs. (2) and (6), we simulated the plasma density during breakdown, as shown in Fig. 4. The results show that it only takes tens of nanoseconds to load down the RF field. The plasma extinguishes at a much slower rate – it is estimated that the density needs to drop to the 10^{10}/cm^3 scale before the cavity would begin to fill again.

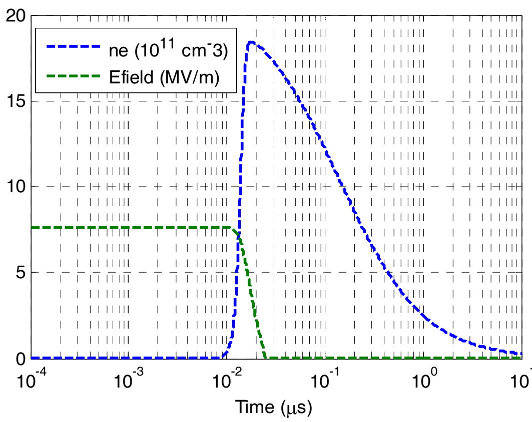

Figure 4: 1-D simulation of the evolution of the electric field and plasma density in nitrogen when the gas pressure is 2 atm and the initial electric field is 7.6 MV/m.

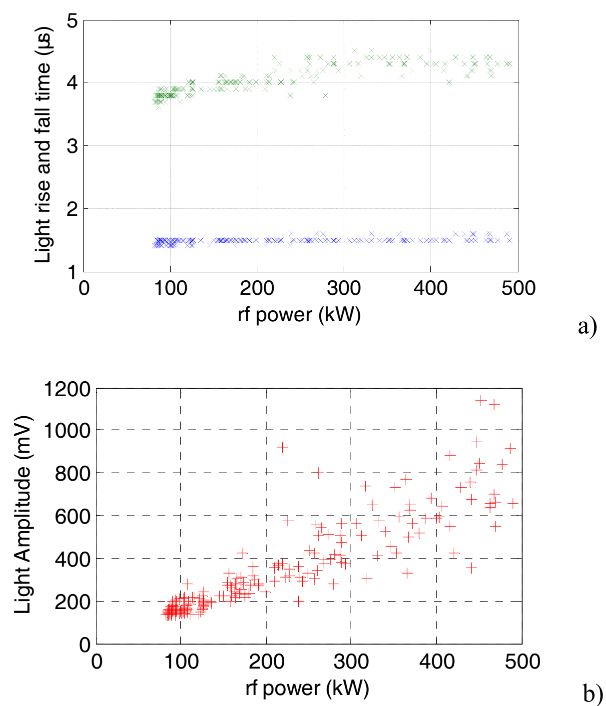

Figure 5: a) The blue and green cross marks are the 90% rise and fall times of the light pulse, respectively; b) the light amplitude versus input power.

To explore how the input power affects the plasma level, we measured the light signal after breakdown at different input power levels. The rising edge of the light pulse indicates how fast the plasma builds up, which should be governed by the second Townsend coefficient of N_2. The rising edge is seen to be independent of RF power, as illustrated in Fig. 5a, but the measurement is

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bandwidth limited by our electronics and much larger than the prediction. The falling edge indicates how fast the plasma recombines and is governed by the recombination rate of the ions, which should have no correlation with RF power, as seen in Fig. 5a. The measured fall times are in rough agreement with the simulation.

The amplitude of the light indicates the density of plasma, which is proportional to the stored energy of the cavity and thus the RF input power – this can be seen in Fig. 5b.

To investigate how the input power affects the plasma after breakdown, we kept supplying power to the cavity after breakdown for different durations (on-times). The results are plotted in Fig. 6, where the light amplitude shows no correlation with RF on-time, as excepted since this power is not able to fill the cavity, which is still detuned by the plasma during this period.

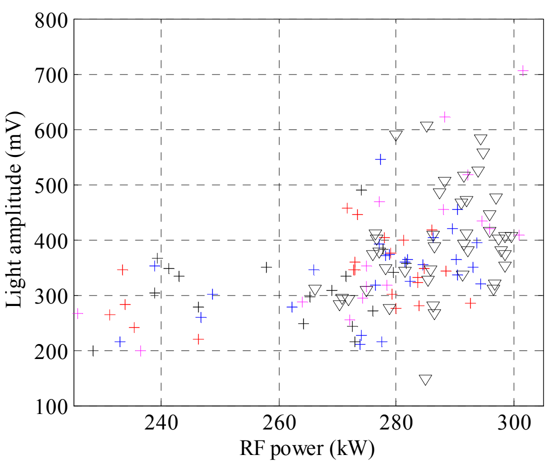

Figure 6: Effect of RF on-time after breakdown on the breakdown light amplitude, versus RF input power, where the blue, red, black and magenta pluses and triangles are, respectively, for RF on-times of 2.6, 3.2, 4.2, 5.6 and 11.5 microseconds.

CONCLUSION

Initial tests of the L-band TE_{01}-mode cavity have been carried out. Preliminary results indicate that the plasma builds up very quickly and remains on more than 10's of microseconds after a breakdown. A 1-D model of the gas discharge in the cavity was employed to dynamically study its progress. We will continue the tests to investigate the surface-independent gas discharge phenomenon and will carry out a full 3-D PIC simulation of the gas breakdown.

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