LASER TRIGGERED RF BREAKDOWN STUDY USING AN S-BAND PHOTOCATHODE GUN

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Abstract

A laser triggered RF breakdown experiment was carried out with an S-band photocathode gun at Tsinghua University for attempting understanding of the RF breakdown processes. By systematic measurement of the time dependence of the breakdown current at the gun exit and the stored RF energy in the cavity, one might gain insight into the time evolution of RF breakdown physics. A correlation of the stored energy and field emission current has been analysed with an equivalent circuit model. Experimental details and analysis methods are reported.

INTRODUCTION

The ultimate performance of high power and high gradient metallic vacuum RF devices is limited primarily by RF breakdowns, which occur on the surface of vacuum metallic structures. RF breakdown is a very complicated physical phenomenon. Despite previous extensive experimental and theoretical efforts, the nature of RF breakdown appears to be largely unpredictable leading to difficulties in conducting a systematic and conclusive investigation [1, 2]. Recently, a novel experiment to study RF breakdown using an intense laser was carried out at Tsinghua University [3]. The breakdown location, breakdown rate, as well as the charge of the explosive emission could be manipulated by the laser.

The collected current at the gun exit, as well as RF signals were recorded in the experiment by a high sampling rate scope when a breakdown occurred. An equivalent circuit model has been developed to study the time evolution of RF breakdown events. This model can well rebuild the evolution of the stored RF energy inside the gun and also reveals how the power redistribute between cells after the explosive emission during breakdown, which sometimes might lead to a secondary breakdown.

EXPERIMENTAL SETUP

The laser triggered RF breakdown experiment was conducted at one of the S-band photocathode gun beamlines at the Accelerator Laboratory of Tsinghua University.

The 1.6-cell gun operates at 2856 MHz π-mode with an RF pulse length of 6 µs, rise time of 2 µs, and fall time of 2 µs. The cathode surface of the gun is a solid, demountable copper plate. With 4.8 MW input power, the available RF field on the central area of the cathode surface can be as large as 58 MV/m. In normal operation a UV laser (wavelength 266 nm, pulse width 1.2 ps full width at half maximum, 1 mm^2 spot size on the cathode and 2 mJ maximum energy) is directed onto the central diamond polished area of the cathode to generate photoelectron emission. For the laser triggered breakdown experiment, the laser was directed at the cathode ~0.5 µs before the end of the flat top when the cavity had been fully filled. The mirror inside the vacuum chamber was remotely controlled to vary the laser position on the cathode. A schematic layout of the experiment is shown in Fig. 1. All signals were sampled at 50 Gs/s by a 12 GHz bandwidth digital scope synchronized to the laser signal or the input RF signal when the laser pulse was absent.

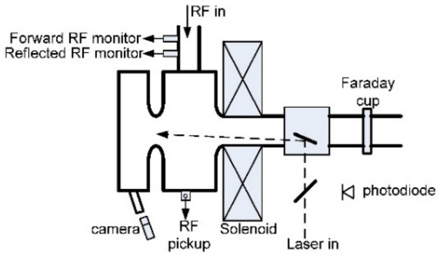

Figure 1: Layout of the experiment setup.

EXPERIMENTAL RESULTS

RF Breakdown with a Laser Trigger

When Operated with the laser trigger, the gradient on the cathode was limited to 48 MV/m. Under this condition, when the laser intensity was very low (<5 µJ), the normal photoemission process occurred without breakdown. When the laser energy was increased, RF breakdown happened more frequently. At laser pulse energy over 100 µJ, RF breakdown occurred at almost every RF pulse.

A short time Fast Fourier Transformation (FFT) is applied to analysis the scope data. The onset of the fundamental mode collapse, the appearance of higher order modes (HOM), and the starting time of the captured breakdown current agree well with each other. In

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particular, the 8.6 GHz HOM is found to be excited by the explosive emission. Its frequency is close to the third harmonic of the fundamental mode, thus it can be coherently reinforced by the bunch train (separated by one RF period of fundamental mode) within the emission current. The onset of a breakdown can then be defined at the moment of excitation of this HOM.

All the breakdown events can be classified into two types according to the breakdown current profile from the Faraday cup, which are the single-breakdown type (only one current pulse) and the multi-breakdown type (two or more pulses within an interval of ~200 ns). Multi-breakdown events were quite rare and less than 10 of them were recorded of a total of 1000 RF breakdown events. Typical recorded waveforms are shown in Fig. 2.

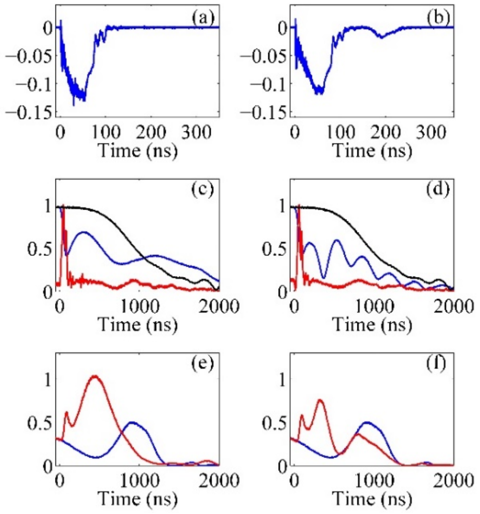

Figure 2: RF breakdown with laser trigger of single-breakdown event (left) and multi-breakdown event (right). (a-b) The Faraday cup signal in Amperes. (c-d) Normalized FFT amplitude of the pickup signal in different frequency bands as a function of time, including the fundamental mode without breakdown (black line), the fundamental mode with breakdown (blue line), and the 8.6 GHz HOM with breakdown (red line). (e-f) Normalized FFT amplitude of the reflection signal, including the fundamental mode without breakdown (blue line) and with breakdown (red line).

Apart from the 10 ns window FFT method to study the evolution of fundamental mode and HOMs, another FFT method with longer window (2000 ns) and thus higher frequency domain resolution (0.5 MHz) is also applied to study the frequency shift of the gun after the onset of RF breakdown. Results show a 1.5 MHz frequency downshift in signal-breakdown events and no frequency shift in multi-breakdown events. The former case is easy to understand as plasma propagating along the axis (high E-field region) detunes two cells to a lower frequency. But the latter case has yet to be understood. It seems that the second breakdown detunes the cells to a higher frequency and hence cancels the frequency downshift by the first breakdown.

RF Breakdown without a Laser Trigger

Tens of RF breakdown events without the laser trigger were also recorded for comparison. Similarly to laser-triggered ones, two types of RF breakdown, excitation of the 8.6 GHz HOM, as well as frequency detuning after the emission are observed without the laser trigger. However, there is a 40~140 ns time delay between the start of the collapse of the fundamental mode and the excitation of the HOM. Also, multi-breakdown ones dominate all recorded breakdown events (~70%). These differences will be discussed in the next Section. Typical recorded waveforms are shown in Fig. 3.

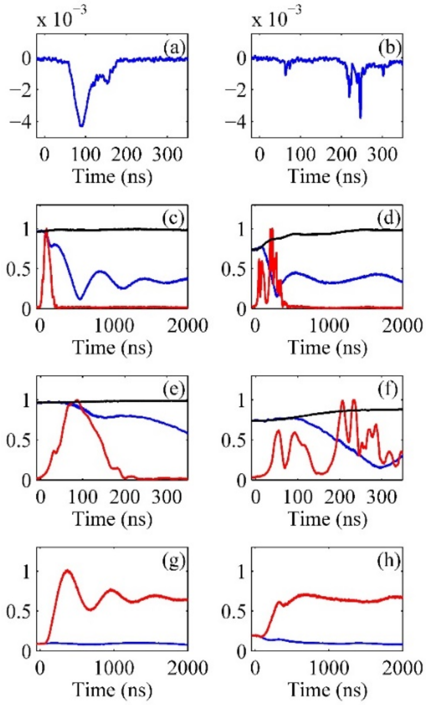

Figure 3: RF breakdown without laser trigger of single-breakdown event (left) and multi-breakdown event (right). (a-d) Same curves as Fig. 2.(a-d). (e-f) Same signals in (c-d) with a zoom in view around 0 ns. (g-h) Same curves as Fig. 2.(e-f).

EQUIVALENT CIRCUIT MODEL

To study the evolution of the fundamental mode after the onset of breakdown, an equivalent circuit model is developed. The gun is modelled as two coupled RLC resonators excited by an external RF power [4] and the emission current is modelled as two extra sources whose phases are opposite to the corresponding cell voltages, as Fig. 4 shows.

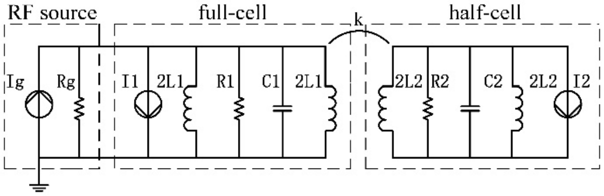

Figure 4: Equivalent circuit model of the gun with two explosive emission current sources.

Based on the FFT results with 2000 ns window, frequency detuning of the two cells is also introduced to the model. The actual plasma propagation and influence on cavity resonance are very complex. To simplify, in the model, the onset of frequency detuning is chosen based on the speed of plasma movement and best match with the observed RF signal during the breakdown.

For laser triggered RF breakdowns, as the breakdown occurred on the cathode, the half cell is set to be detuned by a certain value immediately after the EEE. The highest ion speed v_s in the cold explosions was obtained to be 2×10^4 m/s [5]. Theoretical work analysed the arrival time spectra of the ions and showed that ions can reach even higher speeds when the thermal energy is increased [6]. Accordingly the full cell is set to start detuning 200 ns (corresponding ion speed of 1.5×10^5 m/s) after the onset of the breakdown and linearly shifted lower to a certain value. By choosing the magnitude of the two currents to be 18 A and the frequency shifts to be 3.2 MHz and 0.9 MHz for the half cell and full cell respectively, the simulation of the circuit model could reproduce the signal-breakdown waveforms, as shown in Fig. 5(a) and Fig. 5(c). The frequency of the π-mode is then downshifted by 1.7 MHz, also agrees with the FFT result. The stored energy in the full cell and half cell before the onset of breakdown is 0.91 J and 0.40 J respectively. The calculated energy absorbed by the explosive emission current is 0.78 J in the full cell and 0.39 J in the half cell. The simulation of multi-breakdown events is more complex and a second detuning to the half cell after the onset of the second EEE is introduced as discussed before. The upper shift is set to 1.3 MHz and the simulation shows reasonable agreement with experiment results, as shown in Fig. 5(b) and Fig. 5(d).

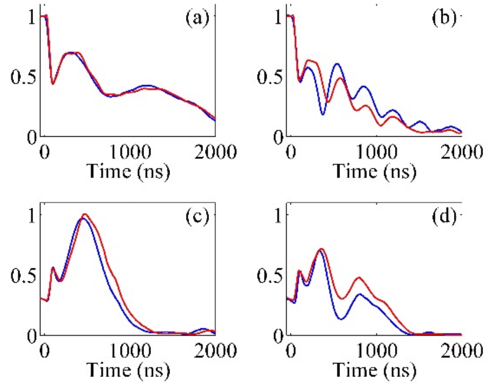

Figure 5: Comparison of simulation (red line) and experimental results (blue line) of single-breakdown event (left) and multi-breakdown event (right). (a-b) Normalized pickup signal. (c-d) Normalized reflection signal.

For RF breakdowns without the laser trigger, if only the breakdown current source in the half cell is present, the time delay between the onset of the fundamental mode collapse in the full cell and onset of breakdown can be well rebuilt by the circuit model. This indicates the breakdown occurs in the half cell but away from the axis and thus the current is lost on the wall between two cells. Under this condition, only the field in the half cell collapses immediately after the onset of breakdown and it takes a certain period of time for the full cell to respond to the energy imbalance between two cells. As the breakdown spot does not recover from the first emission (caused surface plasma, surface damage, etc.) in such a short time, another breakdown can be triggered in the half cell when the power from the full cell flows in. For multi-breakdown events, the excitation of the HOM caused by the second breakdown is always near the end of the fundamental mode collapse, as shown in Fig. 3(f). This observation also confirms the second breakdown is triggered by the RF power flow. While for laser-triggered RF breakdown events, the breakdown occurs on axis and the current can pass through two cells, absorbing RF energy in them. Thus much less power is fed into the half cell from the full cell. It can explain why multi-breakdown events are much rarer with the laser trigger.

CONCLUSION

It is demonstrated that RF breakdown in the S-band photocathode gun can be triggered by an intense laser pulse at a given position. The time evolution of catastrophic electron emission at the nanosecond scale after the onset of breakdown has been observed and analysed. Subsequent experiments are planned at the Argonne Wakefield Accelerator facility.

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