EXPERIMENTAL STUDIES OF RF BREAKDOWNS IN THE COUPLER OF THE TTF RF GUN

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Abstract

During the TTF-FEL Phase I, the RF gun of the TESLA Test Facility (TTF) has been operated with long RF pulses (up to 0.9 ms) and high RF peak power (up to 3 MW). RF breakdowns have been observed and localized in the RF input coupler. In this report we will present statistics of RF breakdowns for different RF pulse length, peak power and repetition rates from 0.1 Hz to 2 Hz. We will also discuss the origin of these breakdowns.

INTRODUCTION

Fermilab has developed and delivered to DESY two RF guns for the operation of phase 1 of the TESLA Test Facility (TTF) linear accelerator. The first RF gun (designated *G3* in the following) has been operated in TTF from October 1998 to April 2002. *G3* presented a reliable behavior with short RF pulses ($< 300\ \mu$s). However, for longer RF pulse lengths, the gun suffered more and more from RF breakdowns reducing the effective beam time. At the point, where the breakdown rate was not acceptable for the test of TESLA accelerating structures, a second RF gun (*G4*) has been installed in June 2002. Gun *G4* has been operated at the Fermilab/NICCAD photoinjector test stand from 1999 to March 2002 with short RF pulses (typically 30 μs) and at DESY until November 2002 with long RF pulses (900 μs). The forward power was usually 2.8 MW with a repetition rate of 1 Hz. For this study, different pulse lengths and repetition rates ranging from 0.1 Hz to 2 Hz have been used. In contrast to the operation at Fermilab, breakdowns have also been observed with *G4* at DESY, fortunately with a much lower rate than *G3*. This paper will describe the dependence of the breakdown rate on the RF pulse length, forward power, and repetition rate. The origin of these breakdowns will be discussed as well.

RF GUN DESCRIPTION

The Fermilab RF gun consists of a 1 1/2-cell (1.625) OFHC copper structure resonating in the $TM_{010,\pi}$ mode at 1.3 GHz. It is a high duty cycle RF gun designed to handle 800 μs long RF pulses with 4.5 MW of peak power and at 10 Hz repetition rate. In this regime, an average power of 36 kW is dissipated in the cavity walls. This heat is removed by water flowing in cooling channels machined in the cavity walls. The cooling system allows a water flow of 4 l/s at a pressure of 6 bars.

The RF is fed into the cavity through a sideways mounted waveguide at the full cell by a coupling slot. A layout of the RF gun and the coupling slot is shown in reference [3].

BREAKDOWNS OBSERVATION

A layout of the RF system of the gun is presented in Fig. 1. It consists mainly in an oscillator (1.3 GHz), a vector modulator, a pre-amplifier, and a klystron. Details about the feedback loop can be found in [2] and [3].

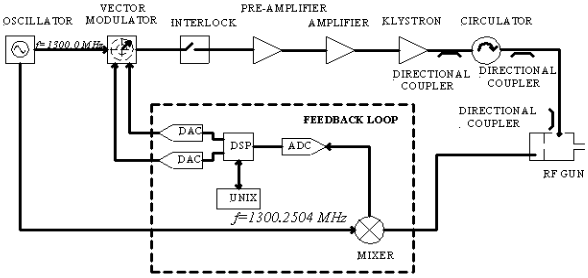

Figure 1: Layout of the RF distribution system.

As indicated in Fig. 1, an interlock module is installed at the exit of the vector modulator. In case of an interlock this module stops the RF immediately within the pulse. Fast interlock channels are: a photo-multiplier mounted at the vacuum side of the RF input coupler, an electron detector at the SF_6 side of the RF window, reflected RF power from the gun measured with a diode through a directional coupler. Other slower interlocks are: vacuum pressure, SF_6 pressure, RF window temperature.

If a breakdown occurs, the reflected RF power increases rapidly. An interlock is triggered at a threshold of 150 kW, which inhibits RF within a μs. This prevents further development of the breakdown event and limits damage to the gun. This interlock does not block the next or further RF pulses to reduce dead time.

Breakdown statistics is acquired by a script interfacing the TTF control system. It stores the RF pulse shape sampled by a 1 MHz ADC. An example of the collected statistics over 600 pulses is shown in Fig. 2. It shows a histogram of the distribution of the time of breakdown in respect to start of the RF pulse. In this example, 10 % of the 600 RF shots had a breakdown, which mostly occurred within 30 μs.

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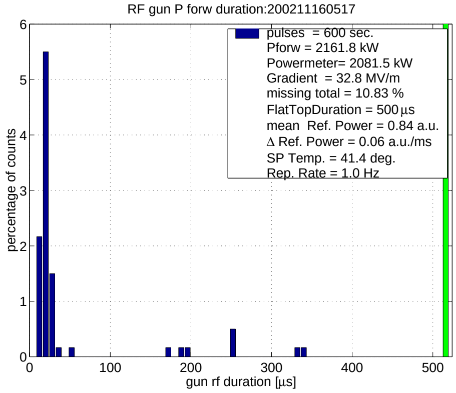

Figure 2: Example of breakdown statistics. The histogram shows the distribution of the time of breakdown in respect to start of the RF pulse. In this example, 10 % of the shots had a breakdown, which mostly occurred within 30 μs.

BREAKDOWNS STATISTICS

We measured the dependence of the breakdown probability as a function of forward power, RF pulse length, and repetition rate.

Figure 3 shows the percentage of breakdowns in respect to the number of RF pulses, measured as a function of the forward power. In this experiment, the RF pulse length is 500 μs, the repetition rate 1 Hz. In Fig. 3(a), a sharp rising edge and in (b) a smooth rising edge of the RF pulse is used. A sharp edge is achieved, when the RF pulse from the klystron is not modified, the amplitude and phase feedback is switched off. The fill time of the gun is approx. 3 μs. A smooth rising of 75 μs is obtained by modeling the forward power with the low level RF system, feedback loops closed. Each point of measurement in Fig. 3(a) is the average of two sets of measurements, each set having a statistics of 600 RF pulses. The arrows in Fig. 3(b) indicate the direction of measurement. From this data, we deduce that the breakdown events appear at a forward power of $\sim$1 MW. In the case of a sharp rising edge, the probability of breakdowns increases with the forward power: from $\sim$13 % at 2.2 MW to $\sim$24 % at 2.8 MW. In the case of a smooth edge, we see a similar percentage of breakdowns up to 2.3 MW (about 20 %), but then a decrease to $\sim$14 % occurs for higher forward powers. From this measurements we deduce, that operating the gun with a sharp or smooth rising edge of the RF pulse does not impact the breakdown probability at least up to 2.3 MW. The decrease of breakdowns for higher forward power is probably due to further conditioning of the gun. This is supported by the observation, that while reducing the RF power, much less breakdowns occurred (circles following the arrows in Fig. 3(b)).

Figure 4 shows the breakdown probability as a function of RF pulse length for a constant forward power of 2.2 MW and a repetition rate of (a) 1 Hz and 2 Hz, and (b) 0.1 Hz. Each point represents a statistics of 5 measurements, each

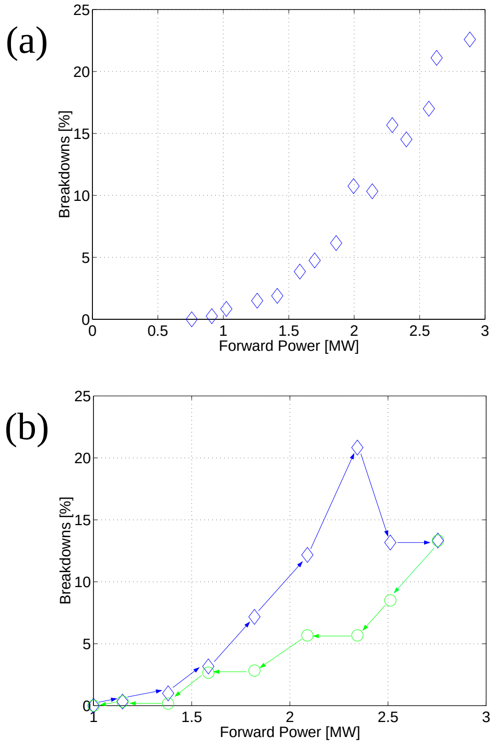

Figure 3: Breakdowns statistics versus forward power for an RF pulse length of 500 μs, a repetition rate of 1 Hz and a (a) sharp and (b) smooth RF pulse rising edge.

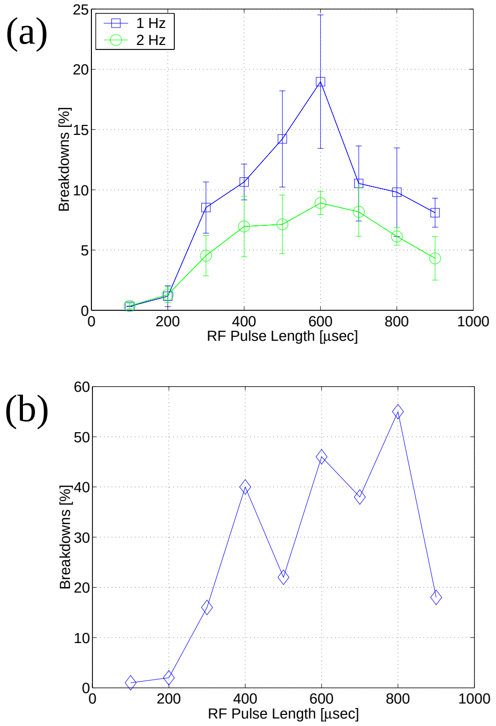

Figure 4: Breakdowns statistics versus the RF pulse length for a forward power of 2.2 MW and at (a) 1 Hz and 2 Hz (b) 0.1 Hz repetition rate.

measurement being a statistics over 600 RF pulses.

Breakdown starts to show up at an RF pulse length of more than 100 μs. The breakdown probability reaches a maximum at 600 μs. This behavior has been observed in different measurements; it is therefore not due to a conditioning effect. Comparing the breakdown rate for different repetition rates (Fig. 4(a) and (b)), it is interesting to notice, that the breakdown rate is inversely proportional to the repetition rate.

ORIGIN OF BREAKDOWNS

Piezo-electric ultrasonic sensors are used to locate the breakdowns in the RF gun [1]. The breakdowns generate an acoustic signal. Their amplitude and arrival time is measured with several sensors spread out over the outer surface of the gun and waveguides. The breakdowns have been located in the RF coupling slot, between the waveguide and the full cell.

Statistics on the breakdowns observed during the experiments presented in the previous section show (Fig. 2 as an example), that independently of the repetition rate, the forward power, the pulse length or the sharpness of the RF pulse, the breakdowns occur mainly between the 10th and the 30th μs of the RF pulse.

In the following, we try to explain this behavior. During the tuning of the RF gun, the coupling slot edges have been kept sharp. We estimate the roundness of these edges to be in the order of 0.1 mm. HFSS simulations show, that in the presence of RF power in the gun cavity, the edges facing the interior of the cavity are exposed to a strong surface magnetic field in the order of 375 kA/m (for 2.2 MW of RF power, 900 μs pulse length). This magnetic field induces eddy currents which induces heat. It is dissipated into the metal and induces stresses. Figure 5 shows ANSYS [4] simulations of the temperature and corresponding stress distribution in the coupling slot (part facing the interior of the cavity; RF 2.2 MW, 900 μs). The peak temperature is 420°C with a stress of 170 MPa. We think that the abrupt increase of the surface temperature of the copper and its associated stress is the most probable reason for the breakdowns. In fact, we suspect field emission created at surface cracks opened due to the repetitive stress. Multipactoring or sparks develop, which then led to a reflection of the incident power. Similar effects have been observed at copper RF structures at SLAC and are presented in details in [5].

A new design of the coupling slot with more round edges and using tungsten [6] could cure the breakdown problem. The melting point of tungsten is three times higher than copper.

CONCLUSION

RF breakdowns have been observed in the Fermilab RF gun for RF powers of more than 1 MW and RF pulse length of more than 100 μs. These breakdowns have been located in the coupling slot between the waveguide and the full cell. They are most probably caused by RF pulse heating inducing an abrupt temperature rise and the development of local stress. The breakdown probability increases sharply with the RF power and does not depend significantly on the sharpness of the rising RF pulse edge. The breakdown rate is inversely proportional to the repetition rate, going from 20 % at 0.1 Hz to 8 % at 2 Hz. After the end of the TTF phase 1 runs, both RF guns have been sent back to Fermilab, where these studies will be continued.

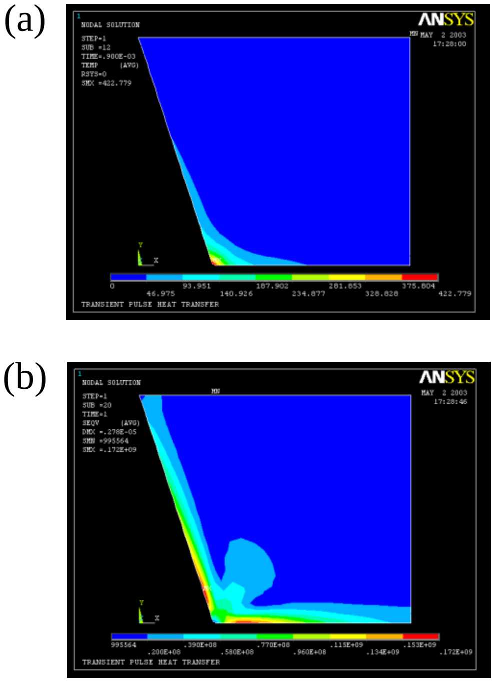

Figure 5: ANSIS simulation of the (a) temperature (°C) and (b) stress (Pa) distribution around the coupling slot edge. Forward RF power = 2.2 MW, RF pulse length = 900 μs.

ACKNOWLEDGEMENT

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