

QUANTITATIVE OUTGASSING STUDIES IN DC ELECTRICAL BREAKDOWN

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Abstract

Breakdown in the accelerating structures sets an important limit to the performance of the CLIC linear collider. Vacuum degradation and subsequent beam instability are possible outcomes of a breakdown if too much gas is released from the cavity surface. Quantitative data of gas released by breakdowns are provided for copper (milled Cu-OFE, as-received and heat-treated), and molybdenum. These data are produced in a DC spark system based on a capacitance charged at fixed energy, and will serve as a reference for the vacuum design of the CLIC accelerating structures.

INTRODUCTION

CLIC accelerating cavity performance is limited by the breakdown rate observed at the required accelerating fields. Breakdowns can kick the beam and blow up the emittance, possibly leading to beam loss. A severe potential problem is also the outgassing following a breakdown, causing a local pressure rise which, depending on the amount of gas released, might cause instability for the following bunches or following pulses, ultimately making the rest of the beam unstable [1].

A DC breakdown system has been available at CERN for several years now [2]. Its purpose is to perform breakdown studies in ultrahigh vacuum (UHV) at a higher turnaround (about one week to test one sample) compared to the RF testing facilities. The environment is much simpler and the breakdowns are more easily monitored than in the RF setup. The set-up uses a tip (anode) to plane (cathode) geometry. A fixed voltage is applied from a charged capacitance, with an energy comparable to that of a breakdown in the RF cavities, which is around 1 J.

There are two main modes used in the DC Spark Test System – spark cycle mode and breakdown rate mode. In the former mode, a given voltage is applied. If no breakdown is detected, the voltage on the capacitor is increased and the new voltage is applied to the electrodes. In case of a breakdown, the voltage is registered and the cycle is reset to a starting voltage, usually sufficiently low to avoid any breakdown. This is a time-consuming measurement, but the reproducibility of the results is good. For a breakdown rate measurement, a fixed voltage is applied repeatedly to the electrodes. Whether or not a breakdown took place is registered after each attempt.

The electrodes are located inside a baked-out UHV chamber of approximately 12 L. There is a quadrupole residual gas analyzer (RGA) connected to the chamber. It has been calibrated against a filament gauge for nitrogen

and hydrogen, and calibrations for other gases were extrapolated from the standard tabulated ionization factors compared to nitrogen. In order to properly measure the pressure rise after a breakdown, the pumping speed was reduced drastically by pumping through a small bypass. The pumping speed was $S_{N_2} = 0.023$ L/s for nitrogen.

In addition to the quantitative investigation of the gases released from breakdowns, there is also interest in studying any dependencies on surface conditions. Amongst others, it is expected that the conditioning seen for some materials could be an effect of removing surface impurities or oxides. This study could give further indications to such a hypothesis.

RESULTS

Copper Electrodes

Copper and certain copper alloys (e.g. CuZr for its fatigue strength) are amongst the most promising materials for accelerating structure manufacturing. A preliminary study found five different main gases that were typically present after an electrical breakdown: H_2 , CH_4 , CO , CO_2 , and sometimes H_2O . At the surface one could indeed potentially find water remnant even if a bakeout has taken place, because of dynamic production through H diffusion through the bulk. Similar experiments in the past have also reported findings of Ar [3], which are not confirmed here. An important source of error is that the total pressure increases after a breakdown, and so the current on the RGA for any mass to charge ratio could increase due to crosstalk and not necessarily because of an increase in its amount.

The hydrogen current for a spark cycle measurement is shown in Figure 1. The ratio of other gases compared to hydrogen remains almost constant during the experiment. In this figure, the energy for each spark is given in order to observe correlations between energy in the spark and peak current in the RGA. The DAQ time step of the RGA was 2 seconds, and the gas released is calculated from the integrated RGA current after a breakdown. This is not necessarily directly proportional to the peak current. The total uncertainty is estimated to be approximately 25 %. Notice that there are sometimes significant amounts of gas released on pulses before a breakdown (visible in the tail preceding the outgassing peaks) which occur probably due to field emission currents.

In breakdown rate measurement mode, the applied voltage (and thus the field) was fixed to a level where 100 % breakdowns were expected, and the gap was fixed so that

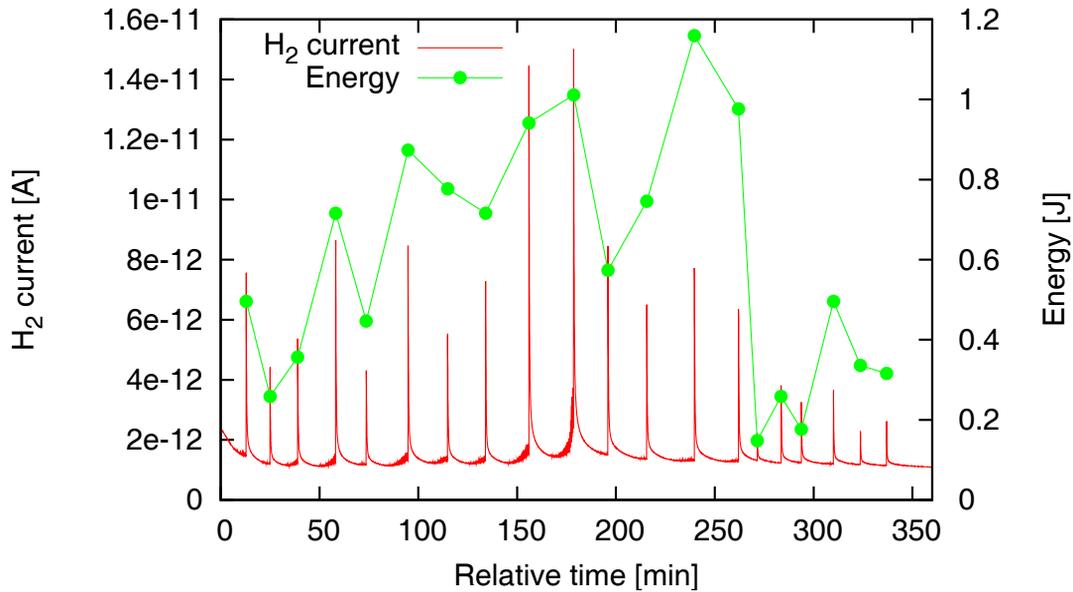


Figure 1: Hydrogen current in a spark cycle experiment. In this measurement, a stepwise voltage increase results in a field emission current prior to a breakdown. This can sometimes lead to significant pressure increase (current is proportional to the partial pressure). The energy in each spark is given for comparison and its value is read on the right hand y-axis.

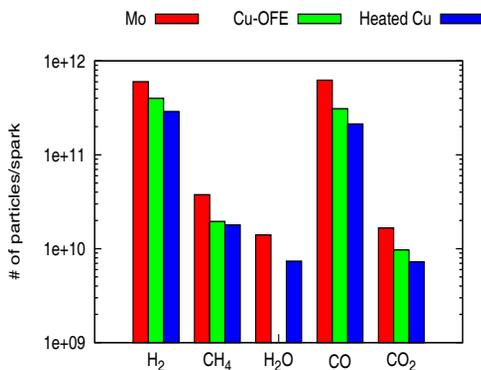


Figure 2: Number of molecules released in one breakdown attempt for molybdenum electrodes (red), copper electrodes (green) and copper electrodes that had undergone a heat treatment. A higher voltage is used for the molybdenum electrodes because of the higher breakdown resistance.

the energy was always 0.8 J, not taking into account electrode gap variations following breakdowns (which are usually small for copper). This is approximately the energy per RF pulse for the current CLIC parameters. A 5 min waiting time was inserted after each breakdown in order to let the vacuum pressure stabilize again. This experiment requires about 2.5 h for 30 sparks. Hydrogen and carbon monoxide are the most prominent gases, followed by methane and carbon dioxide. Statistical variance between different sparks in the absolute number of molecules released is found to be around 10 %. Values obtained are within range of what has been found earlier for copper electrodes [3]. Experimental results are summarized in Figure

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A minor improvement in the number of gas molecules released is also seen when the electrodes have undergone prior to installation a heat treatment, which follows the CERN standard copper brazing cycle (815 °C for 2 h in vacuum) [6].

Molybdenum Electrodes

In the DC Spark Test System, molybdenum has shown a better breakdown resistance than copper [4]. Since its other properties so far do not exclude it as a candidate cavity fabrication material (conductivity, fatigue strength, ease of fabrication etc.), molybdenum has gone through a thorough review in the DC Spark Test System. In contrast to copper, molybdenum electrodes show a clear conditioning period during which the gradient increases until it reaches a stable state. For molybdenum electrodes, this usually takes about 50 sparks. This could be due to surface impurities or oxides that are cleaned by the sparks [5] or by melting and stress relieving of the surface. The outgassing results shown in Fig. 3 however do not help drawing a conclusion on this issue. For each registered breakdown in this measurement (the light blue curve), the amount of the four given gases (same four as for copper) are calculated. The amount of gas released seems to fluctuate around the same constant level during and after conditioning. This result might instead support the hypothesis that gas release is due to electron stimulated desorption (ESD) from the anode or the experimental chamber.

The average population of the four different gases is also given in Fig. 2. The breakdown rate was set to 100 % as before, and the electrode gap was decreased to get an energy

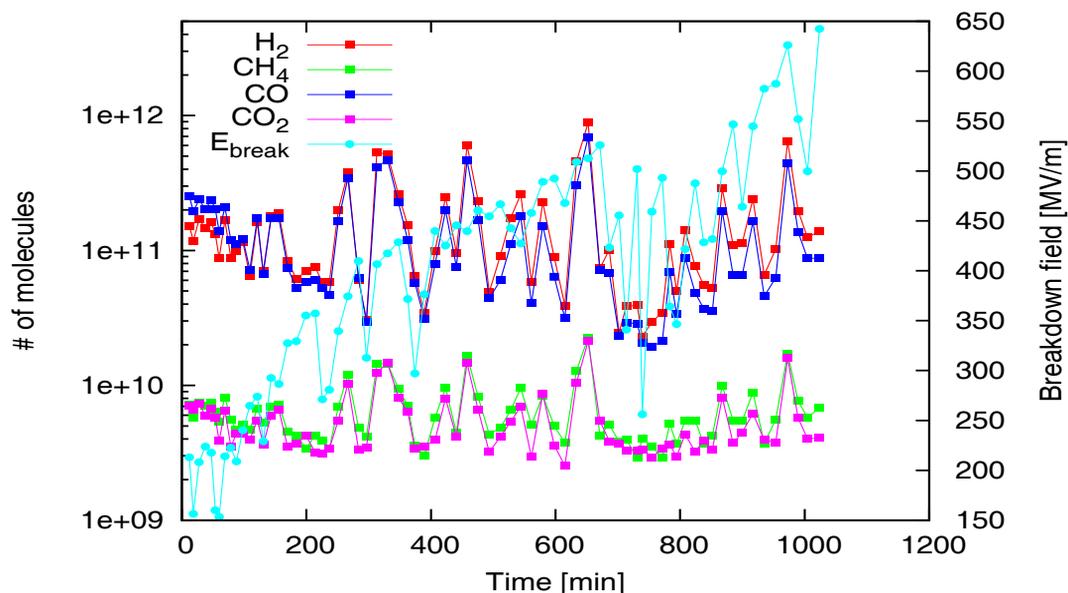


Figure 3: Outgassing during conditioning of the molybdenum cathode. The anode was already conditioned. Each point is given as the amount of gas released at that breakdown, with the corresponding breakdown field given on the right hand vertical axis.

in each spark of 0.95 J. The electrodes were conditioned beforehand. The result should thus be directly comparable with the results for copper. Since the same calibration and experimental setup is used, only the statistical error remains. The statistical uncertainty is found to be 9 – 11 % for both experiments, leading to the conclusion that the gas released from different materials is the same within experimental error.

SUMMARY

These studies indicate that copper and molybdenum electrodes give only small differences in vacuum quality due to breakdowns, the difference between materials could just be statistical deviations. On average, the amount of gas released corresponds to about a monolayer over a $100 \mu\text{m}^2$ area. A remaining open question is if the registered gas is coming directly from the electrodes, or if it is produced as secondary particles from the chamber walls. This hypothesis could lead to an explanation of the somewhat surprising fact that no changes have been observed during conditioning for molybdenum electrodes.

One should note that there could also be other gases coming out of a spark, especially the bulk material. However, such metal ions have a sticking factor close to one. Since the RGA is not in line of sight to the electrodes, these will not be registered. Even with the electrodes within sight, these particles would not be registered because of the RGA resolution time of 2 s. In order to see the ions coming directly from the electrode gap, other tools would be necessary such as a Faraday cup.

The results from these studies will be used as a reference for vacuum simulations of the CLIC accelerating

structures, studying the time constant for vacuum recovery after a breakdown. The present limitation as defined in the CLIC parameters, is the estimated vacuum requirement of 10^{-8} mbar [1]. The vacuum should be below this value before the next bunch train arrives at the location. It is not yet known if this is a conservative requirement, but ongoing simulation results have shown that with the outgassing values reported here, the beam should not be perturbed.

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