

# RF BREAKDOWN OF METALLIC SURFACES IN HYDROGEN\*

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## Abstract

In earlier reports, microscopic images of the surfaces of metallic electrodes used in high-pressure gas-filled 805 MHz RF cavity experiments were used to investigate the mechanism of RF breakdown of tungsten, molybdenum, and beryllium electrode surfaces. Plots of remnants were consistent with the breakdown events being due to field emission, due to the quantum mechanical tunnelling of electrons through a barrier as described by Fowler and Nordheim. In the work described here, these studies have been extended to include tin, aluminium, and copper. Contamination of the surfaces, discovered after the experiments concluded, have cast some doubt on the proper qualities to assign to the metallic surfaces. However, two significant results are noted. First, the maximum stable RF gradient of contaminated copper electrodes is higher than for a clean surface. Second, the addition of as little as 0.01% of SF<sub>6</sub> to the hydrogen gas increased the maximum stable gradient, which implies that models of RF breakdown in hydrogen gas will be important to the study of metallic breakdown.

## INTRODUCTION

RF cavities pressurized with hydrogen gas are being developed to produce low emittance, high intensity muon beams for muon colliders, neutrino factories, and many other applications. The high-pressure gas suppresses dark currents, multipacting, and other effects that are complicating factors in the study of breakdown in usual RF cavities that operate in vacuum. Measurements using the test cell described below in strong magnetic fields have shown that pressurized gas allows higher gradients than can be achieved in vacuum cavities with similar parameters [1,2]. In the studies reported here, various metals are tested in a pressurized cavity where RF breakdown is expected to be due primarily to the interaction of the metallic surfaces with the electromagnetic fields.

## APPARATUS

A schematic of the 805 MHz Test Cell (TC) geometry is shown in Figure 1. The TC is a cylindrical copper-plated stainless steel pressure vessel. RF power is fed into the chamber via a coaxial line Replaceable hemispherical electrodes of various materials (Sn, Al, Cu, Mo, Be, W) are separated by a 2 cm gap. The characteristics of the cavity and the MTA experimental conditions have been described previously [1]. The data described here were taken at the same time as data reported in another paper at this conference [3].

After exposure to the RF fields, the metallic Al, Cu and Sn samples were examined using a High-Scope Advanced

Microscope (Hirox<sup>†</sup>) and scanning electron microscope (SEM) to determine if breakdown events are associated with characteristics of the material surfaces.

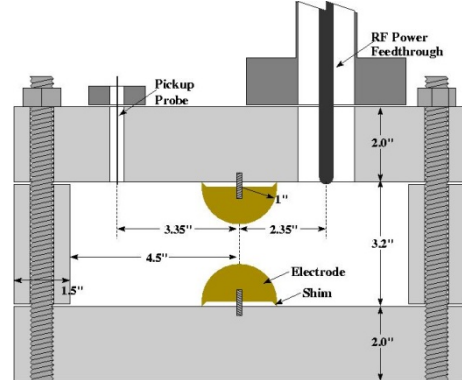


Figure 1: Cross-section of the Muons, Inc. Test Cell.

## EXPERIMENTAL RESULTS

The experimental results of maximum stable RF gradient as a function of hydrogen pressure for Al, Cu and Sn are shown in Figure 2. The usual model for this is that increased gas density reduces the mean free collision path for ions giving them less chance to accelerate to energies sufficient to initiate showers and avalanches.

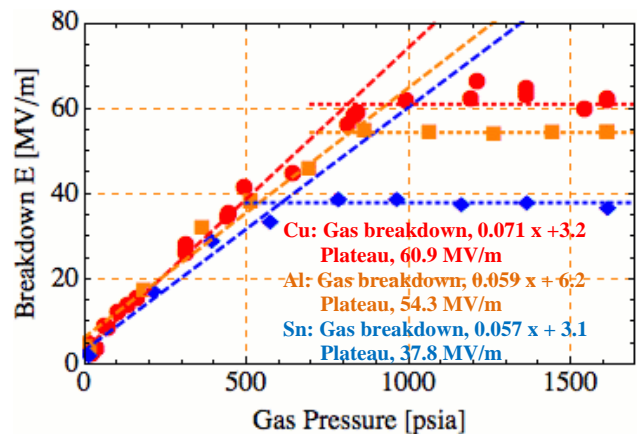


Figure 2: Maximum stable TC gradient as a function of hydrogen gas pressure for Al, Cu and Sn.

This model applies to the linearly rising gradient as the pressure is increased. At some point, the gradient becomes high enough to cause the metallic surface to

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break down and the maximum gradient does not increase as the pressure is increased further. As shown in Figure 2, it is found that Cu electrodes operated stably with surface gradients near 60 MV/m, Al near 54 MV/m, while Sn achieved values near 38 MV/m. The three electrode materials were run at their maximum voltages for several hours.

### Melting point and breakdown voltage

The Maximum gradient for all materials, Al, Cu and Sn, from the data set reported here is shown in blue on figure 3 along with Cu, Be, Mo, and W in red from previous measurements in terms of melting point.

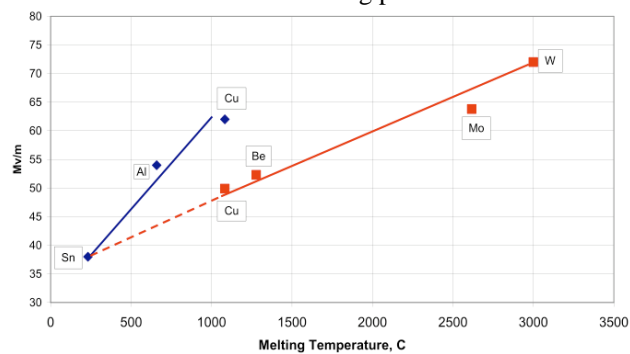


Figure 3: Breakdown voltage vs melting point of various electrode materials. Red squares are older data, blue diamonds are the data reported here.

It should be noted that the melting point is unlikely to be the actual independent variable, since a straightforward calculation indicates the energy deposited in a breakdown event should lead to a different dependence [4]. However, the melting point should scale with the bond strength. And the bond strength should be related to other relevant parameters like fatigue limits, as suggested by recent work by Dolgashev and Tantawi [5].

An unexpected result was that a new set of copper electrodes which were meant to be an experimental control had a higher breakdown gradient than had been seen in previous experiments with a different set of copper electrodes. Surface analysis after the experiments ended indicated that the new copper electrodes were a different grade of copper with surface contaminants of machine oil and sulfur, the latter presumably deposited during the SF<sub>6</sub> doping measurements described below.

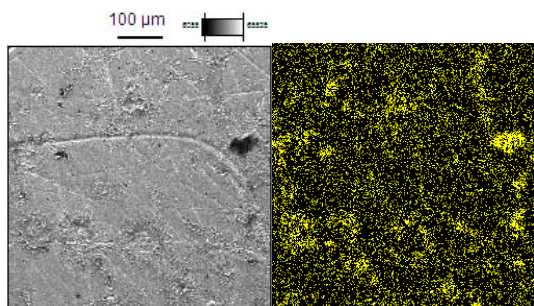


Figure 4: The carbon mapping of the copper surface.

Figures 4, 5, and 6 show the SEM map of Carbon and Oxygen on the copper and aluminium electrode surfaces after the test, respectively. Table 1 shows the Energy Dispersive X-ray (EDX) analysis of the materials on the copper surface. The carbon and oxygen may be from machine oil.

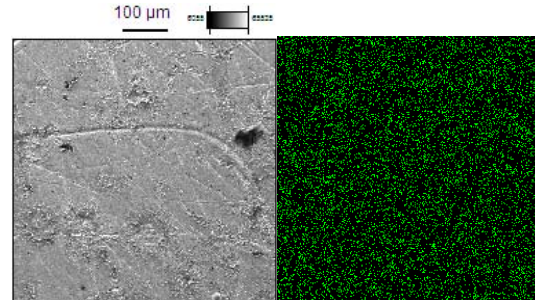


Figure 5: The oxygen mapping of the copper surface SEM

Table 1: Amount of different elements on the Cu surface.

Element	Weight %	Weight % Error	Norm. Wt. %	Atom %	Atom % Error
C	22.67	+/- 0.66	22.67	58.78	+/- 1.72
O	1.64	+/- 0.24	1.64	3.20	+/- 0.47
S	1.93	+/- 0.06	1.93	1.87	+/- 0.06
S	---	---	---	---	---
Cu	73.76	+/- 0.89	73.76	36.14	+/- 0.43
Cu	---	---	---	---	---
Total	100.00	---	100.00	100.00	---

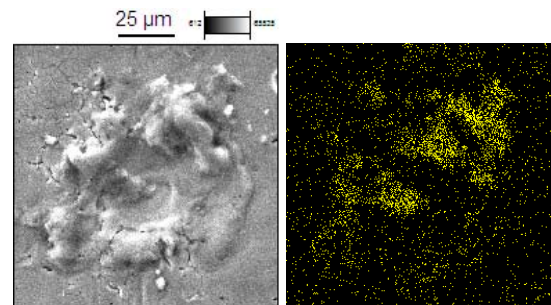


Figure 6: The C mapping of the Al surface



Figure 7: Picture of copper electrode surface after the breakdown experiments. Blue and red discolorations are copper oxides and the white areas correspond to sulphur. The total width of the picture is about 1 mm.

## EFFECTS OF SF<sub>6</sub> DOPING

A companion paper reported at this conference studied the results of the same experiment from the standpoint of the RF breakdown at lower pressures, where the gas properties determine the maximum stable RF gradient.

The measurements shown in figure 2 were done with undoped hydrogen gas. One of the reasons that the surfaces may have been contaminated as described above, was that studies carried out in parallel and reported elsewhere at this meeting were testing the use of SF<sub>6</sub> as a means to improve the ability of hydrogen-filled RF cavities to work in the presence of intense beams of ionizing radiation. The breakdown of the SF<sub>6</sub> during these experiments probably accounts for the trace amounts of sulphur shown in table 1.

However, the results of the maximum stable gradient versus pressure studies with the dopant have clearly shown that one of the hypotheses that has inspired the use of pressurized cavities as a means to study RF breakdown is not correct. Namely, it was believed that the pressurized gas would absorb dark currents and thereby allow the study of breakdown of metal surfaces to be simplified such that the major variables would only be the metallic surface and the electromagnetic fields.

The unexpected result can be seen in figure 8, which shows the usual plot of electric gradient versus pressure for the case of the aluminum electrodes. The red points correspond to the case of pure hydrogen gas and the green points to the case of 0.01% SF<sub>6</sub> doped hydrogen. As shown in the companion paper, the rising slope at low pressure, the Paschen region, is improved by an amount that is predicted by a simulation model of gas breakdown with SF<sub>6</sub> doping.

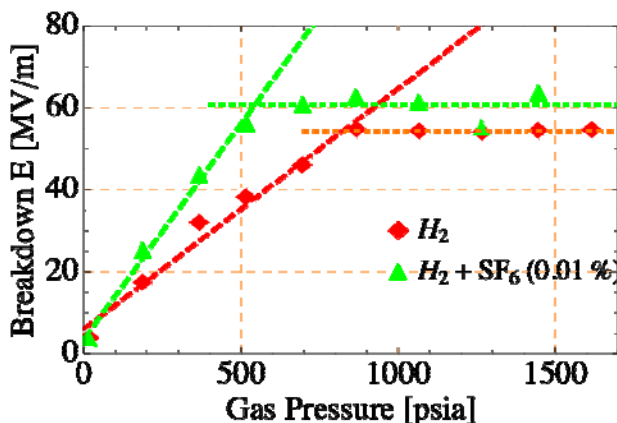


Figure 8: Observed breakdown as a function of gas pressure and dopant in aluminum electrodes.

The higher pressure regions of the figure, where the breakdown gradient does not change with pressure, show that the maximum stable gradient is significantly affected by the SF<sub>6</sub> dopant. This effect is also seen in the studies of the copper and tin electrodes.

Earlier studies of the plateau region of various electrode materials did not show any obvious differences between

hydrogen or nitrogen gas and that led credence to the idea that the gas has little effect on the metallic breakdown phenomena. These SF<sub>6</sub> doping studies have demonstrated that not to be the case, and models of metallic breakdown in pressurized cavities will have to include the gas. As shown in the companion paper [3], gas models can be developed and tested in the Paschen region and already have some satisfying agreement with experimental data. A new 1.3 GHz test cell has been constructed that will allow breakdown studies under pressurized and vacuum conditions [6]. This will allow the experimental investigation of theories of RF breakdown over a wide range of parameters [7].

## CONCLUSIONS

Systematic studies of breakdown in pressurized cavities are continuing to investigate the role of bond strength, as described by melting or boiling point, in determining the maximum stable RF gradient. The latest studies were inconclusive because of contamination of the electrode surfaces. Unexpectedly, the contaminated copper surface allowed a higher maximum gradient that was earlier achieved with a clean surface.

New measurements of the effects of SF<sub>6</sub> doping imply that gas composition can have a significant effect on the maximum stable gradient in the plateau region of the gradient versus pressure curves. Breakdown models in pressurized cavities will have to include the details of the gas interaction.

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