# High Voltage Vacuum Insulation in Crossed Magnetic and Electric Fields

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*Abstract*

Research on high-voltage vacuum insulation has been conducted using several test stands to support development of an improved electrostatic deflector for the Chalk River superconducting cyclotron. One test stand uses a magnetic field of 0.5 T normal to the electric field. It is instrumented with isolated electrodes above and below the negative high-voltage electrode, an isolated anode and monitors of X-rays, light emission and residual gas analysis. This test stand has been used to study high-voltage conditioning and microdischarge phenomena for gaps from 1 to 3 mm. Copper and stainless steel with a variety of surface treatments have been used during these experiments. Results from this research have led to improved understanding of high-voltage conditioning in "practical" vacuum systems that reach about $2*10^{-7}$ torr with no bakeout capability. DC electric fields as high as 67 kV/mm (100 kV across a 1.5 mm gap) have been obtained with vacuum degassed and electropolished copper electrodes. Other surface preparation have been tested and results are compared in this paper.

## I. INTRODUCTION

The electrostatic deflector of the Chalk River superconducting cyclotron operates in a magnetic field of 2.5 to 5 T. It has been observed [1] that operation of electrostatic deflectors in a strong magnetic field can reduce the peak electric field compared to operation without magnetic field. A test stand has been built [2] that permits high- voltage tests with a 0.5 T magnetic field normal to the electric field. Tests have been made with stainless steel and copper electrodes with and without magnetic field. No significant differences have been found attributable to the magnetic field. However, the well-instrumented test stand has been used to obtain valuable insight into vacuum high-voltage insulation.

## II. TEST STAND

Figure 1 shows details of the test stand that was used for these measurements. Negative high voltage is provided by a 100 kV supply that is fed through one of the insulators developed for the Chalk River superconducting cyclotron [2]. The anode is mounted on a moveable solid rod that is isolated from ground with 1 kΩ resistor and a protective spark gap. The electrodes were made from 1.9 cm diameter by 1 cm long cylinders with a 2 mm radius on the outer edge. Isolated sparking plates are positioned above and below the electrodes and the magnetic field has the orientation shown in Figure 1. A glass window is mounted on the side of the chamber for visual or X-ray measurements. For some measurements, a second insulator and positive 100 kV power supply was used to obtain nearly 200 kV between the electrodes. The chamber was pumped with a turbomolecular pump and maintained a vacuum of about $10^{-7}$ torr. A Residual Gas Analyzer (RGA) was used to measure the outgassing produced by high electric fields.

## III. HIGH-VOLTAGE TESTS

The test stand was used for a number of high-voltage tests. Electrodes made from 304 stainless steel and Oxygen-Free, High-Conductivity (OFHC) copper were subjected to different surface treatments and then tested to the maximum electric field that could be sustained. Two types of 304 stainless steel were used. One was commercial grade 304 and the second was vacuum re-melted.

Typical testing procedures were to set a wide gap (from 1 to 2 cm) and condition the chamber for about one hour to the maximum power supply voltage. Considerable outgassing often occurred during this process. The high voltage was then turned off and the gap re-set to values such as 1 or 1.5 mm for a given test. The voltage was increased

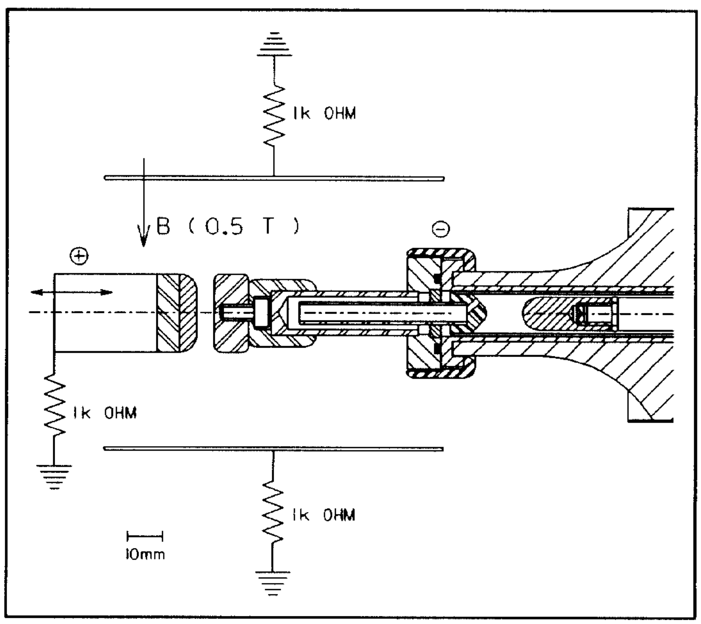


**Figure 1** Details of the test stand.

to about 30 kV in 10 minutes and then in 5 kV increments with 10 to 30 minutes of conditioning between increments. Observations were made of the electrical activity to the sparking plates and anode, X-ray production and the composition of outgassing that occurred as the voltage was slowly increased.

## IV. ELECTRODE PREPARATION

Surface preparation for these tests included as-machined, polishing with an abrasive pad, electropolishing and heat treatment in a vacuum oven. Samples that were heat treated were either electropolished and heat treated or heat treated and electropolished. The heat treatment was to about 850°C in a vacuum that was measured as 2 x $10^{-6}$ torr in a cool region of the oven. Samples were heated for several hours at this temperature followed by a cooldown of about 12 hours. The electropolished samples were rinsed in running tap water followed by a rinse with ethyl alcohol. After these procedures the samples were transferred in air and installed in the test stand.

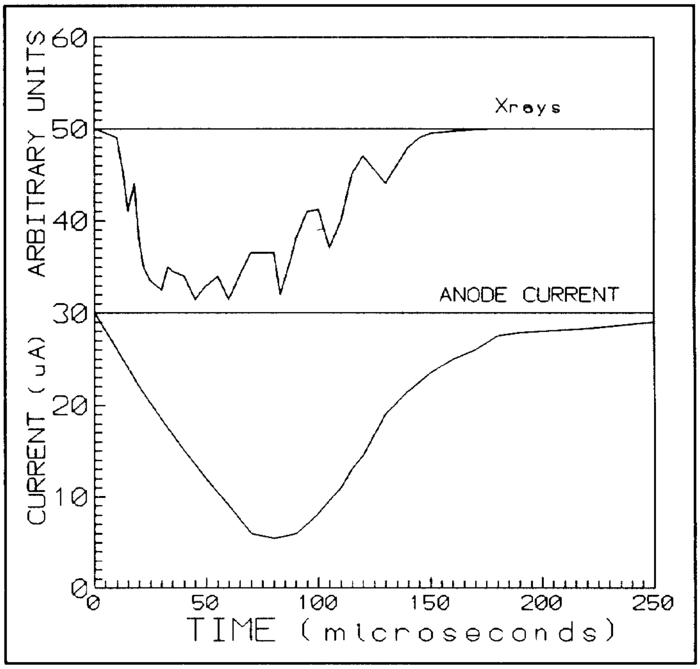


**Figure 2** Microdischarge activity between two electrodes at 2.5 mm gap. The top trace shows x-ray activity. The lower trace shows electrons collected on a sparking plate.

## V. PROCESSES AT INCREASING ELECTRIC FIELD

The processes that occur at electrode surfaces are complex and still poorly understood. Electrical breakdown may be initiated by Field Emitted Electrons (FEE) especially for gaps of less than a few millimetres. The electrons are produced from sites on the cathode and impinge on the anode producing heat and an intense source of X-rays. The intensity of field-emitted electrons increases exponentially with electric field. This can result in electrical breakdown from two sources: the field emitter can explode (explosive emission) producing a cathode plasma or anode heating can cause a plasma to form near the anode. The former is more likely to occur during fast high-voltage pulses while the latter is common for dc high voltage.

Microdischarges are another common phenomenon that occurs between electrodes for gaps from one to many millimetres. These are partial discharges that extinguish without a full breakdown between the electrodes. Figure 2 shows a typical microdischarge between two stainless-steel electrodes at a gap of 2.5 mm and 60 kV. The upper trace shows X-ray production measured with a 1 $cm^3$ cesium iodide crystal mounted on a photomultiplier. The pulse is caused by pile-up of X-rays during the microdischarge. The lower trace is the signal measured on a sparking plate (the magnet was on). The slow rise time and long pulse width suggests that the microdischarge is caused by the motion of gas atoms or ions. Some of these must travel from the anode to the cathode, releasing secondary electrons upon impact because there is always X-rays and visible light produced during each microdischarge. Secondary electrons released from the anode would not produce X-rays. Figure 2 shows no X-ray production after the microdischarge. There is usually no X-ray production before a microdischarge, indicating that FEE production is not a precursor to the process. The magnetic field does not change the shape or the approximate electrical charge collected. Electron collection changes from the anode to the sparking plate and the X-ray yield changes because of geometric considerations.

Residual gas analysis shows that a single microdischarge produces a measurable gas release, mostly of hydrogen (50 to 80 percent) and light hydrocarbons. The gas release per microdischarge has been estimated to be about 5 x $10^{13}$ molecules per burst. Visual observations with a "night vision" camera show that the microdischarges are typically from a few discreet locations. Depending on the details of gas evolution, it may be that this is sufficient gas to support a Townsend type of discharge. The gas density then becomes too small to support the discharge and it extinguishes.

## VI. RESULTS

Microdischarge production occurs for some surface preparations but not all. As-machined surfaces and surfaces polished with abrasive pads usually produce field emission and sparking at low fields and do not produce microdischarges. Electropolished surfaces generally produce microdischarges at moderate fields. Field emission and sparking are then suppressed until significantly higher fields. This is shown by the data in Figure 3. The surface that was electropolished and heat treated produced no observable activity until microdischarges at about 50 kV. When these electrodes were conditioned slowly (3 kV increments every 20 minutes), fields as high as 65 kV/mm were reached before a spark changed the activity from microdischarges to field emission. After the spark, the field was increased slowly until about 77 kV/mm before a destructive spark occurred.

Table 1 shows a summary of some results obtained with copper and stainless-steel electrodes. The table shows the onset of microdischarges ($\mu$dis), field emission (FEE) and the maximum field (max).

TABLE I

| Grade | Process | Gap mm | Electric Field (kV/mm) FEE | $\mu$dis | max |
|---|---|---|---|---|---|
| COPPER | | | | | |
| ETP | EP+HT | 1 | 66 | 50 | 78 |
| OFHC | HT+EP | 1.5 | >66 | 37 | >66 |
| OFHC | AP | 1.5 | 33 | -- | 43 |
| OFHC | AM | 1 | 27 | -- | 45 |
| OFHC | EP+HT | 2.2 | 40 | 30 | 65 |
| OFHC | HT+EP | 3 | 47 | 33 | 57 |
| STAINLESS STEEL | | | | | |
| 304 | EP | 1 | 55 | 36 | 73 |
| 304 | HT+EP | 1.5 | 30 | -- | 63 |
| VRM | EP | 1.5 | 43 | 26 | 55 |
| VRM | HT+EP | 1 | 30 | -- | 75 |

| | |
|---|---|
| ETP | Electrolytic Tough Pitch |
| VRM | Vacuum re-melted 304 SS |
| EP | Electropolished |
| HT | Vacuum degas at about 850°C |
| AP | Abrasive pad |
| AM | As machined |

Several items are noteworthy from this data. The copper electrodes that have been heat treated and electropolished hold higher electric fields than stainless-steel electrodes. The stainless-steel electrodes also reach field emission at lower fields than the copper electrodes. A tedious conditioning process was required to eventually reach the maximum field shown in this table for stainless-steel electrodes.

The two measurements at 2.2 and 3 mm are the first using two high-voltage supplies.

## VII. SUMMARY

A test stand with a 0.5 T magnetic field orthogonal to the electric field has been used for high-voltage tests of copper and stainless-steel electrodes at gaps of 1 to 3 mm. The magnetic field did not produce significant differences in the maximum fields attained but was a useful diagnostic tool in the study of microdischarges.

Surface treatments such as vacuum heat treatment to temperatures of greater than 850°C followed by electropolishing have been used to obtain very high dc fields with copper electrodes. Copper treated in this manner had superior high-voltage performance compared to stainless steel with any surface treatment tested to date. Tests with two high-voltage power supplies have reached breakdown fields as high as 57 kV/mm over a 3 mm gap with heat treated copper.

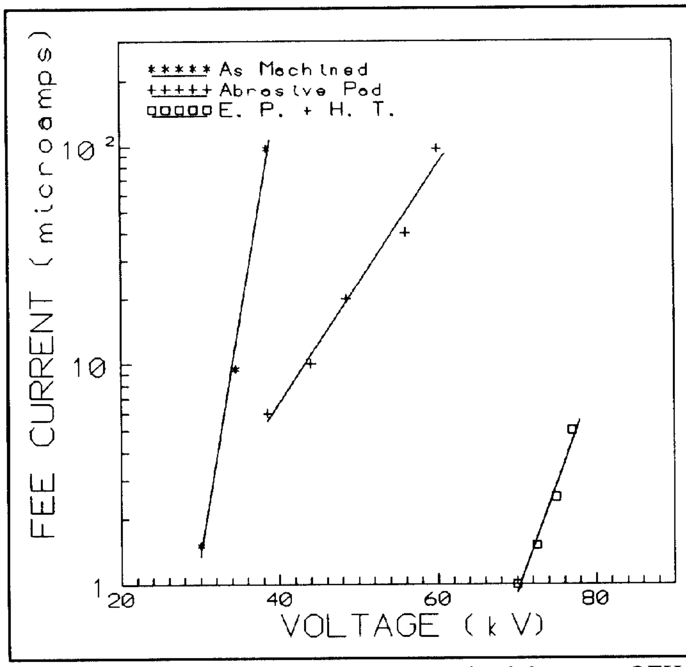


**Figure 3** The maximum voltage sustained by two OFHC copper electrodes for three surface treatments. Repeated sparking occurred at the highest voltage shown for each curve.


## VIII. ACKNOWLEDGEMENTS

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## IX. REFERENCES


[1] W.T. Diamond, C.R. Hoffmann, G.R. Mitchel and H. Schmeing, "Performance of the Electrostatic Deflector of the Chalk River Superconducting Cyclotron", XIV International Symposium on Discharges and Electrical Insulation in Vacuum, Santa Fe, New Mexico, (1990), p. 630.

[2] C.R. Hoffmann and J.F. Mouris, "Model Study of an Electrostatic Deflector Configuration with an Intermediate Electrode", Proceedings of the 13th International Conference on Cyclotrons and their Applications, Vancouver, (1992) p. 577.