THE ELECTROSTATIC DEFLECTOR FOR THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

W.T. Diamond, C.R. Hoffmann, G.R. Mitchel and H. Schmeing
AECL Research, Chalk River Laboratories,
Chalk River, Ontario, Canada, K0J 1J0

ABSTRACT

The electrostatic deflector is the first extraction element in the Chalk River superconducting cyclotron. The design goal of the deflector is a field of 143 kV/cm, to be obtained with a voltage of 100 kV across a gap of 7 mm. This has proven to be very difficult to achieve. The tight space constraints of a compact superconducting cyclotron, high-temperature operation imposed by stray rf fields and problems associated with very strong magnetic fields all contribute to this difficulty. In an effort to reach the design goal, we have investigated many aspects of the physics and technology of high-voltage vacuum insulation. Various choices of materials and surface treatments were tested. The results from this extensive research effort have led to changes in the design of the deflector, and we now routinely exceed the design field, but at a reduced gap of 5 to 5.5 mm. While the reduced gap reduces the transmission for some ion beams, the present deflector performance has led to successful cyclotron commissioning.

1. INTRODUCTION

The electrostatic deflector is a critical component in the extraction system of the Chalk River superconducting cyclotron. It must operate at an electric field in excess of 140 kV/cm for all operating conditions of the cyclotron. These include magnetic fields from 2.5 to 5 T, and residual rf fields from the high power (100 kW) rf system. The deflector, mounted inside a dee, is subject to significant heating from residual rf fields. Tight space constraints limit the maximum vertical spacing to 76 mm, with just over 24 mm between the high-voltage electrode and the sparking plates. These conditions have made progress toward the design goal difficult. We undertook several approaches to improve performance.[1-4] We used the cyclotron as a test bed for some development and built three test stands, including one with a magnetic field, to develop insulators, test electrode materials and study alternative electrode configurations. The wealth of results generated over two years has led to a re-design of most parts of the deflector and, in particular, to the present choice of materials for deflector electrodes. Only the geometrical appearance did not change substantially. The resulting performance level proved sufficient for the cyclotron to be commissioned.

In this paper we give a brief description of the present design and also a summary of some of the results that have led to these choices. Finally, we give a summary of the deflector performance at this time.

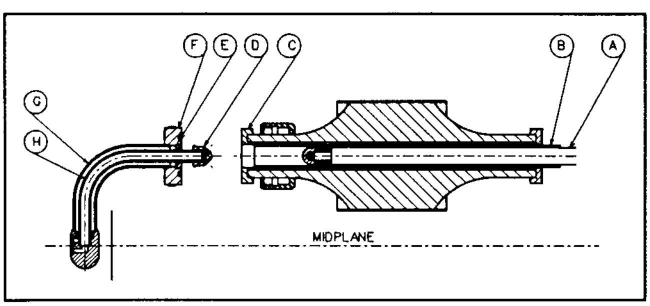

Fig. 1 Cross section of the high-voltage electrode and feed insulator. Details are explained in the text.

2. DEFLECTOR DESIGN

Figure 1 shows a schematic cross-sectional view of the electrostatic deflector, and its feed insulator. We had determined previously that, under the operating conditions of the cyclotron, elevated temperatures of any deflector component led to substantial reductions in performance. Consequently, we decided to cool, as directly as possible, all components that are subject to heating from residual rf or the ion beam. The figure shows in detail how this is done for the high-voltage electrode.

High-resistivity (about 15 MΩ • cm) water is circulated between the high-voltage cable (A) and a teflon tube (B). The water passes through fitting (D) to the high-voltage electrode through tube (H). The electrode is cooled over its entire length. The water returns through tube (G), exits through small holes in (F), and passes on the outside of the teflon tube (B), completing circulation back to the external water system. Flange (C) is part of a teflon liner that is installed inside the ceramic insulator. It captures a smoothly contoured metal fitting that is used to join the insulator to the high-voltage electrode. The teflon is etched and epoxied to the ceramic, with a joint near the center of the insulator. Both the O-ring joint (E), between (C) and (F), and the insulators have proven to be very reliable.

A 2 cm water column between the high-voltage cable and the electrode provides a large (30 MΩ) reliable isolation resistor. Operation without this resistor leads to much greater spark damage and rapid failure of the deflector.

3. REVIEW OF VACUUM DISCHARGE REGIMES

An electrostatic deflector is a vacuum-insulated high-voltage gap operating in a strong perpendicular magnetic field. A vast literature exists on high-voltage discharge phenomena in vacuum gaps, but little research has been done on such discharges in a magnetic field.[5] It is useful to review the physics of discharges, to put our problem into context.

Figure 2 shows the measured breakdown voltage of a plane-parallel high-voltage vacuum gap.[6] Note that this is for an electrode profile minimizing electric field enhancements at the edge and for high-quality electrode materials such as stainless steel or titanium. The breakdown voltage is dominated by different phenomena as the gap is increased. For gaps up to about 1 mm, it increases linearly with gap. The discharge is initiated by Field-Emitted Electrons (FEE) that leave the cathode and cross the gap. The FEE current increases exponentially with the electric field and, at some current, a spark occurs. Sparking may help condition an electrode, leading to operation at higher electric fields. As the voltage is increased, irreversible damage finally occurs.

For gaps greater than a few centimeters, microdischarges limit the breakdown voltage. These involve lumps of material pulled from either electrode by the electric field. They cross the gap and impact on the other electrode. As the voltage is increased, the microdischarge can initiate a spark.

For gaps between 5 and 8 mm, the region of interest to our deflector operation, there is a transition region in which both phenomena may be active. To put our requirements into perspective, a line labelled "deflector operation" in Fig. 2 corresponds to 140 kV/cm for gaps from 5 to 8 mm. It shows that our design goal lies only a factor of 2 below what is achievable under ideal conditions, and in the absence of strong magnetic fields or electrode heating. We calculate a field enhancement of about 15 % for the deflector because the electrodes can not be made with ideal profiles.

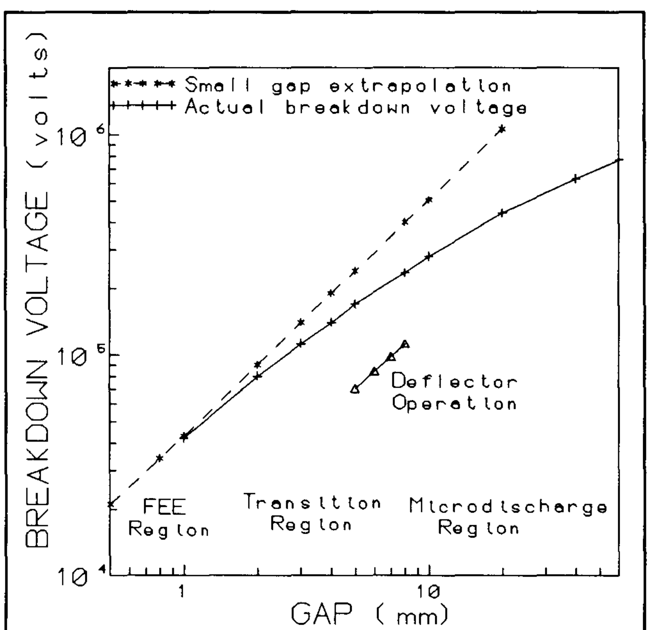

Fig. 2 Breakdown voltage of a vacuum gap as a function of the gap spacing.

For gap dimensions that lie in this region, it is difficult to determine if the precursor for a spark is field-emitted electrons or microdischarge activity. Much of our research tends to support anode-originated microdischarges as an important activity. However, if a damaging spark occurs, a region of enhanced field emission is produced on the cathode. FEE current increases exponentially, with a tenfold increase in current for a 20 percent increase in electric field. This high FEE current generally determines the maximum electric field that can be sustained.

3.1 Test Stand Results

Table 1 presents results of measurements[3] with plane-parallel copper, stainless steel or titanium electrodes for either anode or cathode. Electrodes of 19 mm diameter were machined and polished with 600 grade silicon carbide paper. They were cleaned ultrasonically with detergent and ethyl alcohol and installed with a 2.5 mm gap. After evacuation, the voltage was increased from about 40 kV in 2 kV increments until irreversible damage was done. This is the breakdown voltage shown in Table 1. Typically, 1 to 3 samples were tested for each entry and the data represents averages were more than one sample was tested.

Table 1. Breakdown voltage (kV) for combinations of copper, stainless steel and titanium electrodes.

Cathode Material	**Anode Material**		
	Copper	**Stainless Steel**	**Titanium**
Copper	64	92	98
Stainless Steel	74	96	110
Titanium	72	88	110

The table shows the strong effect of the anode on the breakdown voltage. If field-emitted electrons from the cathode were the main precursor for a damaging spark, one would not expect the large observed increase in breakdown voltage when a copper cathode is matched with a stainless-steel or titanium anode. This conclusion is also supported by data obtained when one or both electrodes are electropolished. These data are shown in Table 2.

Table 2. Breakdown voltage (kV) for copper and stainless-steel electrodes that have been electropolished (E.P.). The gap is 2.5 mm.

Cathode Material		Copper Anode	
		E.P.	Not E.P.
Copper	E.P.	98,96	64
	Not E.P.	85	
Stainless Steel	E.P.		
	Not E.P.	94,94	

Electropolishing both copper electrodes made a dramatic improvement in the maximum breakdown voltage. It was observed that there was a great reduction in microdischarge activity and fewer conditioning sparks as the voltage was increased. When only the cathode was electropolished, there was no improvement, while treating the anode but not the cathode produced a large improvement. Tests with two electropolished stainless-steel electrodes showed only a modest improvement in the breakdown voltage, but there was much less microdischarge activity and fewer sparks as the voltage was increased. This reduced electrical activity in a gap operated at voltages well below the breakdown level is an important consideration in deflector operation.

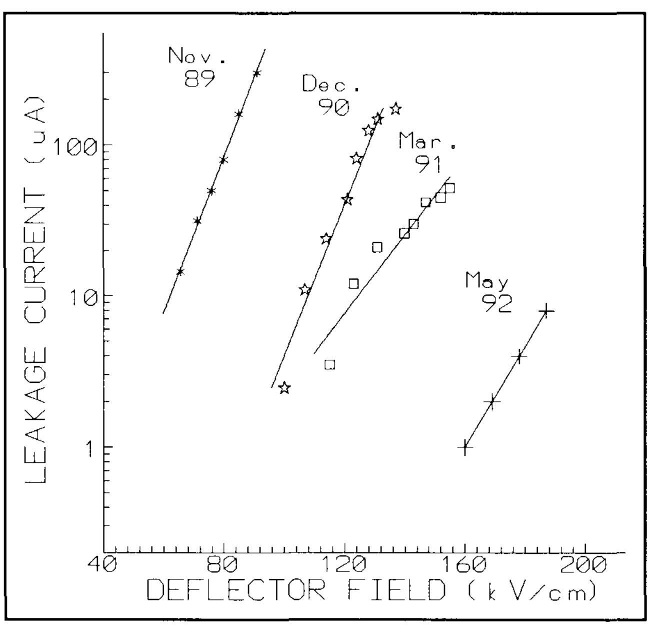

Fig. 3 Lowest deflector leakage current for the dates indicated.

4. DEFLECTOR PERFORMANCE

Results obtained from test-stand experiments have guided the development of the deflector. Significant improvements were made when we replaced the molybdenum used in the original deflector for sparking plates and the septum with stainless steel.[1] This was an unconventional choice of materials which was based on the observation that a spark could result in the transfer of a small sample of molybdenum from the anode to the cathode, where it became the site of enhanced field emission. The observation of increased FEE current for a heated cathode[3] led to the design of the water-cooled high-voltage electrode shown in Fig. 1. The results shown in Tables 1 and 2 pointed to the importance of the anode in high-voltage discharges (with a 2.5 mm gap). We used this as guidance in the choice of electropolished stainless steel for the septum, sparking plates and the supporting rails that hold the septum. Below we summarize some relevant features for optimum performance of the deflector.

The high-voltage electrode was redesigned with a geometry that minimized the electric field enhancements at curved portions and near the ends. We have chosen its thickness and height to be as large as possible, consistent with the restricted space available. Two-dimensional calculations show that there is less than a 15% electric field enhancement for the choices that we have made, but we have not attempted to calculate the field enhancement at the ends where there are compound radii.

It is important to minimize the stored energy in the deflector. We use the water resistor for this purpose.

The vacuum quality of the cyclotron is also important. We observed poor operation of the deflector, which was traced to a minor contamination of the midplane vacuum with roughing pump oil. The oil was cracked into elemental carbon by the rf and deposited on the deflector electrodes. Small flakes on the cathode served as sources of enhanced field-emission. A substantial effort was expended to clean the deflector and the midplane before deflector performance was restored.

The results of all these efforts are shown in Fig. 3. It shows the progress in improving the deflector as a function of time. The data show the best operation at the dates shown. All of the data were obtained with the magnet on at about 3 T and no rf. The deflector gap was 7 mm for the 1989 measurement and about 5 mm for the other measurements. The most recent curve, May 92, was the same with the magnet on or off, but we did not attempt to operate above 85 kV (170 kV/cm) with the magnet and rf in operation. Operation at 85 kV with a magnetic field of 3.5 T and 90 kV with the magnet off were for periods of 18 to 24 hours. The peak performance was at 94 kV (188 kV/cm), and this was achieved for several hours before the voltage was reduced.

The improvement between November, 1989, and December, 1990, was from the change from molybdenum to stainless steel sparking plates and septum, and changes in the geometry to reduce field enhancements. Electropolished cathodes were tested during this period with some success,[3] but anodes were not electropolished.

The water-cooled high-voltage electrode was tested between December, 1990, and March, 1991. This led to better peak performance and increased reliability for operation near the peak levels of performance.

The performance shown for May, 1992, was obtained after a meticulous cleanup following the vacuum contamination that was discussed previously. We also started to electropolish all of the stainless steel anode components during this cleanup. These data were taken during a slow conditioning of the deflector after re-assembly. The conditioning included slow increase of the voltage to 85 kV during a 24 hour period and operation at 90 kV (180 kV/cm) for a second 24 hour period followed by an increase to 94 kV for several hours, all with the magnet off. The voltage was increased to 85 kV with the magnet at 3.5 T for 18 hours and then rf power was turned on. The deflector voltage was lowered to about 40 kV while the dees were conditioned to their operating level. The deflector voltage was then increased to 85 kV with the rf and magnet in operation. This deflector then operated routinely under conditions of high rf power and a magnetic field of 3.5 T during a recent one week experiment at about 135 kV/cm and with only a few μA of FEE current.

5. SUMMARY

A water-cooled high-voltage electrode attached to an alumina feed insulator has been in use for over a year and has operated reliably. We believe that microdischarge activity originating from the anode is an important precursor to electrical breakdown of the gap. Appropriate surface treatments, such as electropolishing both the anode and cathode, appear to reduce microdischarges and sites of field-emitted electrons. We have adopted these procedures for all parts of the deflector that can be treated. We also carefully cleaned the inner surfaces of the dee that form a copper anode and we used a slow conditioning procedure with the magnet off after the deflector had been re-assembled. These meticulous procedures have permitted us to increase the maximum electric field that can be sustained to greater than 180 kV/cm with a 5 mm gap during pre-run testing, and to operate the deflector reliably at electric fields up to 150 kV/cm during cyclotron operation. We intend to test if fields of about 150 kV/cm can be used reliably with a gap of at least 6 mm.

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