ELECTROSTATIC DEFLECTOR DEVELOPMENT AT THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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Abstract

An electrostatic deflector is used to extract heavy-ion beams from the Chalk River superconducting cyclotron. Deflector voltages up to 100 kV across a 7 mm gap (143 kV/cm) are needed to extract the full range of beams that the cyclotron is designed to accelerate. This goal remains a challenge, but substantial progress has been made over the past year. Voltages over 90 kV have been reliably maintained over a 7.5 mm gap with a magnetic field of 3 T. Voltages of 74 kV have been used with a reduced gap of 4.75 mm (corresponding to a field greater than 150 kV/cm) to extract beams with magnetic fields up to 4.25 T. Major progress was achieved when we introduced a water-cooled, negative high-voltage electrode, and changed the sparking plates and the thin septum from molybdenum to stainless steel. Efforts are continuing to attain a field of at least 143 kV/cm over a gap of at least 6 mm width.

INTRODUCTION

The electrostatic deflector is the first extraction element in the Chalk River superconducting cyclotron. The deflector is mounted in a dee and the high voltage is fed down the center of the dee stem. Two insulators, mounted above the midplane, support the high-voltage electrode. Details of insulator design are given in another paper at this conference[1]. The design goal for the deflector was 100 kV over a gap of 7 mm, corresponding to an electric field of 143 kV/cm. The cyclotron operates over a range of magnetic fields from 2.5 to 5 T, and at r.f. frequencies from 30 to 60 MHz. Residual radiofrequency fields can heat the deflector to temperatures above 200 °C. These harsh operating conditions have made it very challenging to reach the design goal. However, electric fields of up to 155 kV/cm over a reduced gap of 4.75 mm have been attained. The smaller gap reduces the extraction efficiency by up to 30 %, depending on the ion beam. However, we have reliably extracted carbon at 50 MeV/amu and iodine at 19 MeV/amu, beams near the upper limit of the mass-energy diagram of the Chalk River superconducting cyclotron.

DEFLECTOR GEOMETRY

The deflector geometry has been described in detail[2,3] previously. Two important changes have been made since then. Overheating was identified[3] as a serious problem. We consequently water-cooled as many grounded parts of the deflector as reasonably attainable, including the lower septum support and the insulator housing. However, experiments on a test stand[3] showed that cathode heating was the most important issue. Subsequently we designed a new water-cooled high-voltage electrode. Figure 1 shows the details. The high voltage is provided by a cable (A) fed down the upper dee stem[1], inside a 13 mm diameter copper tube. High-purity (about 16 MΩ-cm) water is circulated between the high-voltage cable and a thin teflon tube (B), and returned between the teflon tube and the copper tube. The high-voltage cable is terminated with a stainless-steel hemisphere (C). A 2 cm water column provides a 30 MΩ series resistor between the high-voltage electrode and the cable. The teflon tube is inserted from the top of the cyclotron and mated with a tapered end fitting (D) that is part of the high-voltage electrode. The water passes through four small holes in this fitting into a 3.2 mm I.D. copper tube (E) that provides the feed water to the the high-voltage electrode (F). The copper tube joins the stainless-steel body of the deflector electrode in a friction fitting. The return flow is from the upper water channel (G) into the 11 mm I.D. stainless-steel tube (H) that forms the outer part of the coaxial water feed. This tube is welded to the high-voltage electrode (I) and to the threaded fitting (J).

The water channels in the high-voltage electrode were machined into the stainless-steel electrode body, and a 1 mm plate was welded over it. The electrode was then machined on top and bottom to produce the basic outer profile (7.9 mm radius) and rolled to the radius that matches the extraction radius of the cyclotron. The connections to the water-cooled support were machined after the rolling process to avoid distortion.

The feed insulator (K) is made from machinable ceramic (Macor) or alumina. A teflon lining (L) is epoxied inside the ceramic insulator[1], and a smoothly

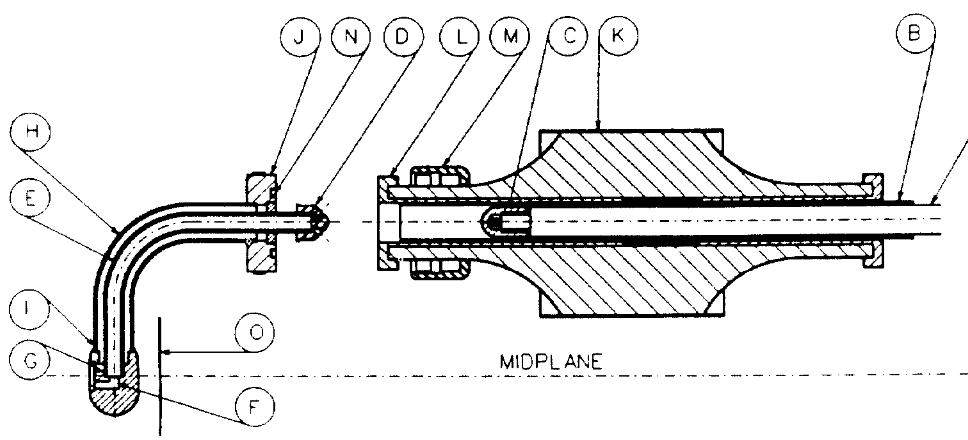

Figure 1. Cross-sectional view of the high-voltage electrode (a) and the high-voltage feed insulator (b). Details are explained in the text.

0-7803-0135-8/91$01.00 ©IEEE

PAC 1991

contoured stainless-steel fitting (M) is captured by a flange on the teflon before the epoxy joint is made. We mount the insulator inside the upper dee and install the high-voltage electrode by making the connection between (J) and (L) with the fitting (M), through removeable access ports in the bottom of the upper dee. An o-ring (N) makes the water-to-vacuum seal. Details of the septum (O) mounting have been given in previous papers[2,3].

A second important change has evolved as a result of our efforts in testing materials for high-voltage properties[3]. Tests using molybdenum sheet as an anode showed severe degradation in voltage standoff after a spark at high electric fields. Small flakes of molybdenum were identified on the cathode after these tests. These flakes likely become new electron-emission sites. Stainless steel performed much better in the same series of tests and has been used for both the sparking plates and the septum for the last 6 months.

DEFLECTOR PERFORMANCE

A previous paper[3] describes the electrical circuit of the deflector, including details of the water column that provides about 30 MΩ series resistance at the high-voltage electrode. A linear voltage-current relationship is observed at low electric fields. This is a measure of the total series resistance, from a fixed surge resistor of 31 MΩ on top of the cyclotron, the water column of about 30 MΩ and the returning water annulus, which typically has a resistance of about 750 MΩ. At high electric field, the leakage current, believed to be from Field Emitted Electrons (FEE), increases more than linearly. The FEE current is observed to increase exponentially with the electric field and it heats the anode surface locally where it hits. At some level, a discharge will occur accross the gap. Such a spark can either reduce the FEE current if it conditions the emitting site, produce no measureable change, or it can severely degrade the high-voltage performance of the gap. The strong magnetic field of the superconducting cyclotron directs the electrons vertically to the sparking plates above and below the high-voltage electrode and focuses them to much smaller spots than electrostatic focusing alone would do. As an example, 70 keV electrons have a gyroradius of only 0.18 mm at a magnetic field of 5 T. This can, in principle, increase the damage from a spark and the rate of evaporation of anode material that is produced at the impact point of the FEE current on the anode. However, our results have shown that magnetic effects are less severe than thermal effects. Most efforts to improve the performance of the deflector have aimed at reducing the FEE current by reducing the peak electric field through careful shaping of the high-voltage electrode, by cooling the cathode surface to reduce thermal enhancement effects[3] and by proper choice of anode material. If the electron emitting sites are located in the vicinity of an insulator, surface charging may occur and metal evaporation from the hot spot on the anode may coat the insulator leading to insulator failure. The insulators on the Chalk River superconducting cyclotron are well shielded[1] and have not suffered particularly from these effects. The deflector has been operated continuously for periods of more than a week with FEE currents as high as 250 microamps. However, recently, these FEE currents have typically been kept at less than about 60 microamps.

Figure 2 shows the measured FEE current as a function of the average deflector field. Four sets of data are shown representing the best performance at the dates given. All data, except those marked March/91, were obtained with the magnet at about 3 T and the r.f. switched off. The March/91 data were obtained with a magnetic field of 4.25 T and the r.f. operating at high power at 58 MHz. The Nov./89 and March/90 data were obtained with a 6.5 mm gap, the Dec./90 data used a 5.5 mm gap and the March /91 data were obtained with a 4.75 mm gap. Some of the improvement has been from this gap reduction. Typically, the maximum voltage that a gap can hold increases only as the square root of the gap width. As the gap is increased, the maximum field will therefore be smaller. Throughout the cyclotron commissioning, we have sought to find a good compromise in the gap width between reasonable beam transmission and the maximum deflector field. A gap of 5 to 6 mm appears to be an acceptable compromise for many beams. We believe that the leakage current originated only from cathodic emmission, and that insulators have not been a limiting factor in our system.

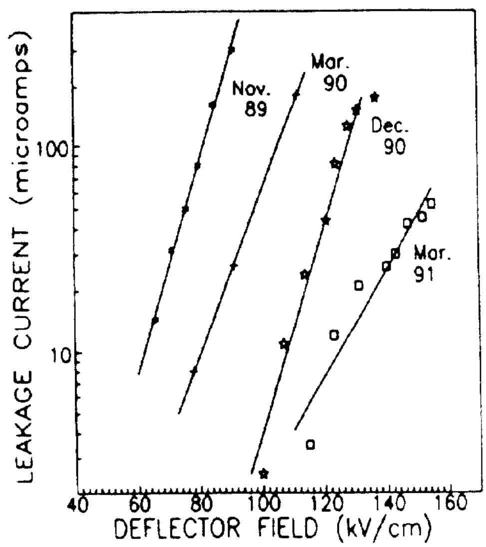

Figure 2. Lowest deflector leakage current as a function of the electric field at several dates during the last 16 months.

The data for Nov./89 and March/90 were described in some detail previously[3]. The high-voltage electrode was then made from solid stainless steel. The increase in the maximum sustainable deflector field that could be obtained at those dates is believed to be mostly from profile changes on the ends of the high-voltage electrode, to reduce the peak electric field, and from changes in the conditioning procedures. Calculations show that the peak electric field is 20 % above the average field for a 6 mm radius at the top and bottom of the electrode. The ends of the electrode have a compound radius involving both the top-to-bottom and side-to-side profiles. The most visible areas of spark damage are generally at the two ends of the electrode. When an attempt was made to use the deflector (March/90 data) to extract a carbon beam at 45 MeV/amu, r.f. heating and beam loading (estimated to be between 10 and 15 watts) increased the leakage current. This lead to a reduction of the maximum useable deflector field by 10 to 15 %.

Many ideas were tested during 1990. An important test-stand result confirmed that sparks between a stainless-steel cathode and a molybdenum-plate anode (the same material in use for sparking plates) transfer small (10 to 50 microns width) flakes of molybdenum to the cathode. Enhanced FEE currents from these flakes reduce the voltage-standoff capability of the gap by nearly 40 %. Molybdenum flakes could not be conditioned away. An experiment in the test stand was repeated three times, in which the same molybdenum anode and stainless-steel cathode were tested to successively higher electric fields until a severe spark lead to a deterioration of the maximum sustainable electric field by about 40 %. In each case, opening the test chamber and cleaning the cathode surface with alcohol, restored the performance. No other cathode or anode change was attempted at this time. These experiments led us to change the septum and sparking plates from molybdenum to stainless steel. This change produced noticeable improvements, with the best result being 90 kV over a 6.5 mm gap. However, r.f. heating lead to a deterioriation in performance back to the previous level.

Attempts were then made to reduce the cathode heating. The first attempt was to use a high-voltage electrode made from solid copper instead of stainless steel. Although test-stand results at that time showed that copper was much poorer than stainless steel for high-voltage standoff, it has much higher thermal and electrical conductivity, which makes it less suseptible to r.f. heating. A solid copper high-voltage electrode with copper hangers was tested. The results are shown on Figure 2, marked Dec./90. To achieve this result, the copper electrode required considerable conditioning (several days of operation at high voltage) with no magnetic field, followed by operation at a magnetic field of about 3 T and then with high-power r.f. present. This electrode was used to extract carbon at 50 MeV/amu, a beam that represented a major milestone for the cyclotron's commissioning because it meets one of the machine's design goals.

The water-cooled high-voltage electrode, described in the first part of this paper, was built and tested as the next development step. Its first operation exceeded the performance of the copper electrode, and it was used to extract ion beams of carbon at 45 MeV/amu as well as chlorine at 35 MeV/amu in an 8-day experiment. After a careful cleanup of the entire deflector and some conditioning, the results shown for March/91 were obtained. This deflector improved with use and helped us to extract iodine at 19 MeV/amu at a gradient of about 150 kV/cm, with a gap of 4.75 mm. It has also been tested to 95 kV with a 7.5 mm gap with no magnetic field present and to 94 kV with a magnetic field of 3 T.

TEST STAND RESULTS

The program to improve the deflector has had considerable guidance from results obtained from a test stand. This test stand was described in detail and some results were reported[3] previuosly. All recent tests point towards the importance of the choice of anode material for peak high-voltage performance. Table 1 shows the results of tests on three materials.

Table 1. Breakdown voltage (kV) for combinations of copper, stainless-steel and titanium electrodes. The gap was 2.5 mm.

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

The tests were made with 19 mm diameter cyclindrical electrodes, with a 2.5 mm gap. All of the electrodes were machined and polished with (wet) 600 grade silicon-carbide paper. The cathode was connected to a low-capacitance power supply with a 2 m long cable. No series resistance was used for these tests and the cable capacitance was about 500 pf. The voltage was raised in 2 kV increments from about 40 kV until a breakdown occurred that produced irreversible damage. Typically, a number of sparks occur as the voltage approaches the breakdown voltage. These sparks can either condition the gap and reduce the leakage current or produce no obvious changes. The breakdown voltage is determined by a spark that typically trips the power supply off. When the voltage is re-applied, continuous sparking will occur at 15 to 20 % lower voltage, an indication of irreversible damage. Good reproducility (about 5 %) has been obtained in tests of some of the combinations.

Table 1 shows the important role of the anode material for a gap of 2.5 mm. The field-emitted electrons originate from the cathode and interact with the anode. The surface properties of the anode (such as adsorbed gas) then play an important role in the breakdown process.

Efforts are underway to apply these results to the deflector. In the present deflector design, the back side of the high-voltage electrode and regions above the hangers that support the high-voltage electrode are copper. Attempts will be made to cover as much of these areas as practical with titanium and to replace the septum and sparking plates with titanium to see if further improvements can be made. A second water-cooled high-voltage electrode will also be fabricated from titanium.

SUMMARY

Improvements incorporated into the deflector of the Chalk River superconducting cyclotron have allowed us to extract ion beams up to 50 MeV/amu, the design goal of the accelerator. Deflector fields exceeding the design goal of 143 kV/cm have been achieved and maintained over a reduced gap of 4.75 mm with some loss in beam intensity. A deflector field of 94 kV across a 7.5 mm gap has recently been achieved both with and without magnetic field, but without r.f. We shall continue to improve this system with the aim of achieving a deflector field of about 150 kV/cm at a gap of at least 6 mm.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the valuable technical help of N. Bray, R.E. Milks, J.F. Mouris, D.R. Proulx and R.R. Tremblay.

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