HIGH VOLTAGE EXPERIMENTS FOR THE ELECTROSTATIC DEFLECTOR OF THE MILAN SUPERCONDUCTING CYCLOTRON

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Summary

The electrostatic deflector for the extraction system of the Milan Superconducting Cyclotron is presently under development. The operating electric field should be up to 140 kV/cm across a 8 mm gap.

In this paper we report the results so far obtained in the breakdown voltage in a 10 kG magnetic field with different types of electrodes in order to select the optimal combination of materials for the cathode and the anode.

The effect of current limiting resistor to control the discharge energy has also been investigated, changing the value of the resistor placed in the circuit between the power supply and the vacuum chamber and also testing a small wire resistor placed directly inside the vacuum, as near as possible to the deflector.

The results of Poisson calculation for the optimization of the HV electrode in order to minimize the electric field value outside the gap region are presented.

Introduction

Two electrostatic deflectors are used for the extraction of the beam from the Milan Superconducting Cyclotron. The design of the extraction system has been extensively described elsewhere[1]. We briefly recall the main properties which have to be fulfilled by the deflectors:

-the maximum operating electric field is of 140 kV/cm in a 8 mm gap.

-they are split into two parts electrically connected, thus allowing a rotation of 5° and they must be radially movable over a 3 cm range.

A preliminary design of the first electrostatic deflector is shown in fig.1.

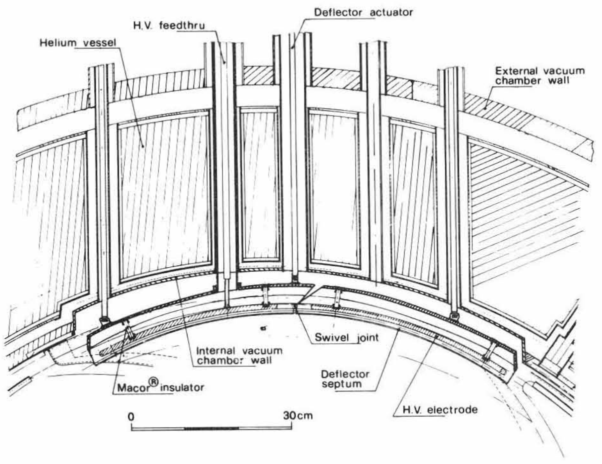

Fig.1 – Preliminary design of the first electrostatic deflector

Severe limitations to the electrical capabilities of the deflectors come from the lack of space of the cyclotron in the extraction region. This allows a vertical and radial clearance of 50 mm. Early tests[2], carried out on a full scale prototype of the first deflector, which is the longest one (750 mm), have indicated that voltage up to 120 kV could be held without magnetic field for long period. Major troubles were observed when the deflector was placed in a 10 kG magnetic field using the magnet of the 45 MeV proton Milan cyclotron. Voltage hold-off capability was reduced to 90-100 kV and after a few discharges permanent damages to the molybdenum spark anodes resulted in a drastic reduction of the flashover voltage to 70 kV. In order to better understand the behavior of the deflector in the magnetic field and to get useful data for the final design a new test stand has been constructed and extensive tests have been carried out with different materials and HV circuit configurations.

Experimental apparatus and deflector prototype.

Experiments are conducted in the test chamber shown schematically in fig.2. It consists of a stainless steel vessel evacuated by a turbomolecular pump to 10^{-4} Pa, placed in the gap of a 6 kG magnet. Two additional low carbon iron plates placed into the vessel allow to increase the magnetic field in the electrode region up to 10 kG. A window in the chamber allows direct observation of discharges through a lead glass shielding. A 150 kV negative power supply is connected to the cathode via a two meter cable with 80 pF capacitance and a series resistance of either 1 MΩ or 30 MΩ. A small wire resistance of 650 Ω can be placed in the supply circuit inside the vacuum chamber after the ceramic bushing. The high voltage feedthrough is a stainless steel tube, 20 mm diameter, with a minimum distance from the chamber wall of 50 mm. This configuration, because of the allowed spacing, is not

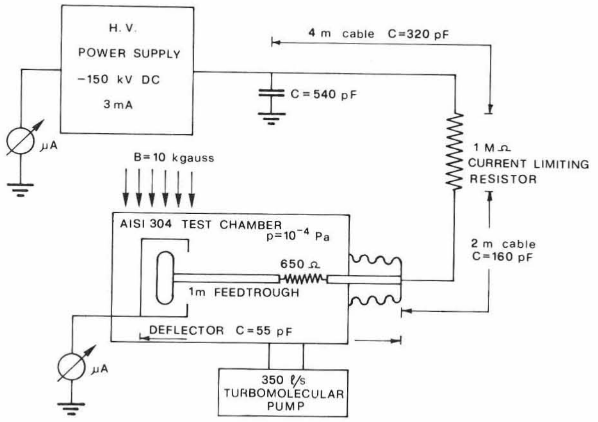

Fig.2 – Schematic diagram of the experimental equipment

critical at all and is considerable different from the operating conditions in the cyclotron; but in these tests we were mainly interested in the electrical properties of the deflector electrodes and insulators.

The HV electrodes are mechanically polished with silicon carbide paper up to 800 grade and then degreased in an ultrasonic bath using acetone followed by chloroform. The degree of microscopic roughness of the surface is typically of 0.25 μm. No significant changes in the voltage hold-off capabilities have been observed in some preliminary tests preparing the electrode to a mirror finish with diamond and alumina pastes having a grain size up to 0.1 μm.

The prototype deflector used in these experiment is shown in fig.3. It has a geometry similar to that adopted in the cyclotron except for the length which is 25 cm, about 1/3 of the final one. The HV electrode is 20 mm high and 10 mm large with the edges rounded with a 5 mm radius. The vertical spark gap is of 15 mm. This shape as discussed later in this paper is not optimized, giving rise to a peak field near the change of curvature which is 40% higher than in the 8 mm gap. Nevertheless we have kept this configuration in order to get comparative data with early tests on the full scale prototype described in ref.2.

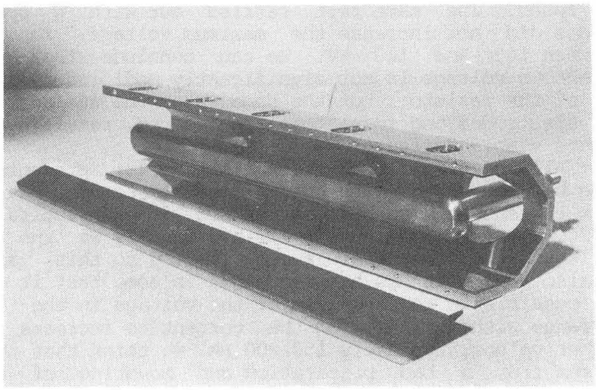

Fig.3 – View of the deflector prototype

The HV electrode is supported by two Macor insulators, 22 mm long, thermally fitted into two stainless steel end caps. A view of the insulator mounting is shown in fig.6. The diameter of the insulators is 10 mm and the surface is threaded. When tested alone, without magnetic field, voltages up to 140 kV have been held. Values in the range 110–120 kV are easily reproducible.

During each test the voltage, the current delivered by the power supply, the X-ray emission measured by a photomultiplier with a NaI scintillator and the magnet excitation current are continuously monitored on a multi-pen recorder.

Some preliminary experiments have been performed to select a suitable material for the cathode. During these tests insulators with a length of 60 mm and a vertical spark gap increased to 40 mm have been used. Electrodes have been fabricated from stainless steel and titanium. When tested without magnetic field breakdown voltages of 135 kV and 150 kV (or more, 150 kV is the power supply limit) have been reached respectively for stainless steel and titanium electrode in combination with a stainless steel septum. No particular difference has been observed with tantalum and molybdenum septa. This result can be explained supposing that sparking, without magnetic field, is mostly a cathode-initiated process. According to these results a combination of titanium and stainless steel, as cathode and septum, has been used in the tests with the magnetic field.

Test in the magnetic field

The electrical properties of the deflector are strongly modified by the presence of a magnetic field, because of the different trajectories of the cathode emitted electrons, which can be focused on small spots on the spark anodes. Moreover the space limitation in the vertical gap, which results in a high electric field strength along the electrode curvature even near the top and the bottom of the electrode itself, gives rise to high field components parallel to the magnetic field, allowing a complete developing of the focusing process. We think that in principle two major effects are dominating:

-a reduction of the voltage hold-off capabilities caused by the thermal effect of the field emitted electrons, which can vaporize and melt the anode hot spot.

-an irreversible damage of the electrodes following a discharge, related to the energy involved in a spark.

Influence of the spark anodes

A suitable choice of the spark anodes material, which results from the combination of several parameters like high melting temperature, thermal conductivity and penetration depth of the electrons helps to increase the electrical strength of the electrode and should limit the permanent damage which occur during a discharge. For these reasons we tested the properties of high melting point materials as tantalum, molybdenum and tungsten. The deflector configuration, already described, had a titanium cathode and a stainless steel septum.

The deflector is conditioned during 12 hours without magnetic field up to 115–120 kV. Current conditioning is routinely done, with the current limited to less then 60 μA, resulting in a final dark current of few μA at 100 kV. A typical current versus voltage curve for a conditioned electrode is shown in fig.3.

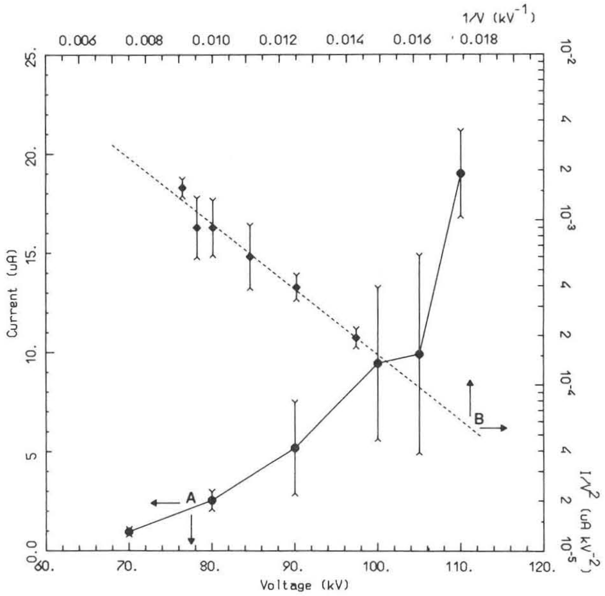

Fig.4 – Typical dark current curve for a conditioned electrode:
A – current versus voltage
B – a Fowler-Nordheim plot with the same values, showing the field emission nature of the dark current

Thereafter a 10 kG magnetic field is switched on starting from 80 kV voltage applied to the deflector. The set value of the voltage is kept for at least one hour and then increased in 5 kV steps until continuous discharge and electrical strength reduction occur. An increase in the dark current up to a factor of two with respect to the measured values without magnetic field is often observed at the moment of the magnetic field switching on.

The relevant results on the maximum voltage held are presented in Table I.

TABLE I

Spark anode material	Maximum voltage held for at least one hour with reliability before permanent damages occur	
	1 MΩ in the circuit	1 MΩ + 650 Ω in the circuit
Tantalum	90- 95 kV	not tested
Molybdenum	100 kV	105-110 kV
Tungsten	105-110 kV	105-110 kV

Visual and microscopical inspections of the spark anodes after a relevant number of discharges at the maximum voltage show a lot of pits and insulators are found strongly metallized. These effects are less pronounced in tungsten. The maximum reached voltage do not differ too much but tungsten seems to be a slightly better material when used as a spark anode, compared with molybdenum and tantalum.

It is rather difficult to establish if the weakest point of the deflector is the HV electrode contaminated by anode evaporation or the insulator itself. We have clearly observed, switching off the magnet after extensive sparking, that often the insulators become critical, and we suppose that this effect is mainly related to the evaporation of materials from the spark anodes occurred when running the deflector in the magnetic field. We have analyzed the contaminants of the surface of the insulator by mean of X rays induced fluorescence technique, and we have found that most of the deposited material comes from the molybdenum or tungsten spark anodes. Only a small fraction of contaminants could come from the stainless steel end caps of the insulator, as iron is also found on virgin insulators. We concluded that no sensible advantage should arise from a better choice of insulating material because the reduction of the voltage hold-off capabilities of the insulator are dominated by the events occurring between the HV electrode and the spark anodes. Since the length of the insulator cannot be increased and an effective shield on the HV side is prevented from space limitation the only attempt we can try is to minimize the electric field on the electrode surface near the insulator in order to decrease the probability of discharge in that region.

The dark current after deterioration of the deflector, if continuous sparking has not been allowed, are not extremely high, ranging between 60 and 90 μA at 90 kV, and reconditioning at lower voltages is effective resulting in a hold-off voltage capability reduced of only a ten kV and sometimes equal to the former; however there is no possibility of reducing the dark current to the original value.

The results so far obtained are considerably different from those observed in early tests of the deflector prototype in the magnet of the Milan AVF Cyclotron. The only significant difference in the experimental arrangement was a three meter longer supply cable after the 1 MΩ current limiting resistance; this increased the stored energy after the resistance of about a factor of two. Turning to a 5 meter cable in the new test stand, we have reproduced the same effects using a stainless steel HV electrode and Mo anodes. A few sparks around 100 kV are sufficient to permanently damage the deflector and it becomes impossible to get voltages of 70 kV and at this level the dark current is excessively high being of the order of 250 μA. This proves that the energy stored in the deflector and supply cables plays an important role in the electrical strength.

Influence of resistance in the HV circuit

Following the suggestion that the irreversible damage to the deflector are strongly related to the energy stored in the system, we have checked the effect of resistance placed in the HV circuit to control the discharge energy. First we have changed the 1 MΩ resistance to a 30 MΩ one but no evidence of improvements have been observed. The 1 MΩ resistance is sufficient in decoupling from the deflector the energy stored between the resistance and the power supply. Also a change of 20 meter in the length of the connecting cable to the power supply does not introduce any variation. Taking into account the experience of SIN[3] we have also tried the effect of a small wire resistance of 650 Ω placed inside the vacuum chamber as near as possible to the deflector. Tests have been carried out with Mo and W spark anodes. The use of this resistance resulted in an improvement of the Mo anodes voltage hold-off capability from 100 kV to 105-110 kV; moreover the pits on the anodes seemed to be much more superficial and no evidence of insulator metallization was found. The same test carried out with W spark anodes did not increase the maximum voltage, ranging between 105 and 110 kV. We can conclude that the breakdown voltage is not significantly modified by the use of the resistor, but the damages on the surfaces of the electrodes and insulators are reduced, resulting in a more stable deflector.

All the experimental results, so far presented, have been obtained with conditioned electrodes having dark currents which did not exceed 60 μA (typically 10-20 μA) at voltages up to 110 kV. Usually we run the deflector with the power supply limited to this value or also lower. It has happened that in some test it was not possible to reach values of the voltage in the 100 kV range without allowing the current to increase to higher values; typically 150-200 μA. We think that this arises from a bad preparation and mounting of the electrodes. The same increase of current can happen suddenly also on a well conditioned electrode, following some critical discharge which gives rise to contamination, which can be seen with the microscope as small melted drops. In both the situations the maximum attainable voltage is reduced but what is remarkable is that the permanent damages produced by the sparks are strongly enhanced. This occurs indifferently with molybdenum or tungsten spark anodes also when we use the 650 Ω resistance. All these effects show that the energy developed in the discharge is not the only responsible for the damage to the deflector but both the stored energy and the high dark current can independently cause the severe deterioration observed.

Optimization of the shape of the HV electrode

The HV electrode geometry tested up to now is not optimized as it presents a very high electric peak field (175 kV/cm at 100 kV voltage) and a high surface field also in the regions which face the spark anodes, which, of course, should be the most critical because of the electric and magnetic field alignment. Moreover also the stainless steel end caps of the insulators have a high field faced to the spark anodes, as seen during the tests in the magnetic field by the pits on the anodes above and below the caps; finally the field uniformity in the gap is rather poor with this shape. Calculations have been carried out with the POISSON code[4] to improve the electrode geometry, aiming to minimize the field in the electrode areas with maximum alignment with the magnetic field, with, if possible, a reduction also in the peak field, which occurs in the actual geometry near the beginning of the curvature, and an improvement of the field uniformity in the gap. Another requirement was not to reduce the insulator length and to allow a mounting less critical than the actual one for the fields facing the spark anodes. Shapes with not more than two radii of curvature for construction simplicity were considered; the most significant are presented in fig.5 with the calculation results shown in fig.6. In fig.5 it is possible to see the new mounting used for the two-radii shapes which allow an insulator length about equal to the former but with the cap recessed into the electrode.

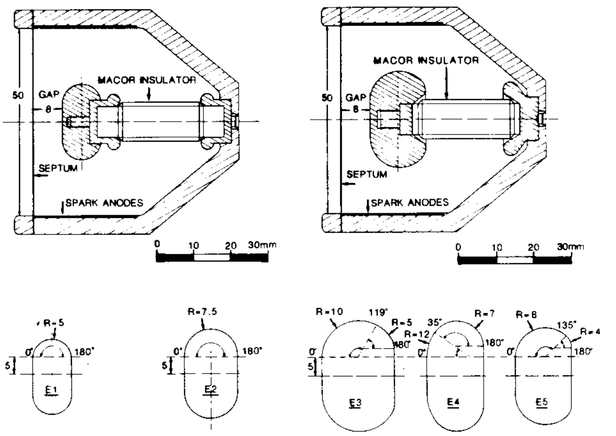

Fig.5 - Section of the deflector prototype with different electrode and insulator geometries:
to the left: constant radius geometry
to the right: two radii geometries

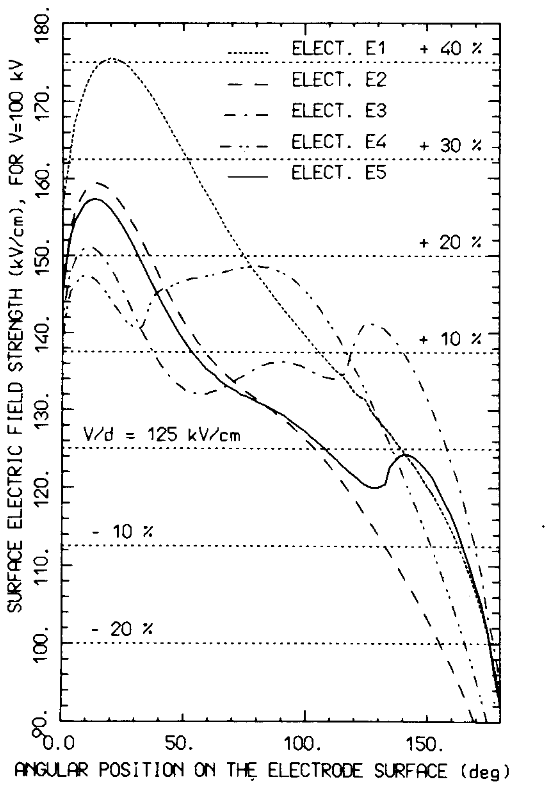

Fig.6 - Surface electrical fields for the five geometries presented, as computed with the POISSON code

Among these geometries the E5 one seems to be the most promising for the lower fields in the top and bottom areas; the E4 would be the best for its minimum peak field but has too high field in the areas more critical in the magnetic field, E2 is very similar to E5 but does not allow an insulator mounting different from the actual one. Some preliminary test carried out with a E5 like electrode have shown that the voltage hold-off capability of the insulator, which was the greatest uncertainty, are at least similar to the old one, both with and without magnetic field. In particular, with tungsten spark anodes and the 600 Ω resistor, after conditioning up to 115 kV, the electrode was able to hold 100 kV in the magnetic field for 4 hours with a minimum current of few μA. After a damaging discharge occurred, the dark current rose to 100-200 μA; nevertheless the electrode was able to hold 105 and 110 kV with current up to 350 μA, each for an hour, and subsequently 112 kV for 20 minutes before continuous arcing occurred. According to these preliminary indications, the new shaped electrodes and insulators will be extensively tested in the future; however it is clear that no geometry change can avoid that sometimes permanent damages to the electrode or to the insulator occur.

Conclusions

In this paper we reported the results obtained in the electrical breakdown tests on a model deflector. Different materials have been used for the HV electrodes and the spark anodes. The optimal combination is titanium for the high voltage electrode and tungsten for the spark anodes, with a small wire resistance placed in the supply circuit inside the vacuum chamber. Mo as spark anode, with this resistance behaves very similarly to W, but the latter seems to result in a more stable deflector. With these experimental conditions voltages of 105-110 kV have been reached and held for a few hours, with the magnetic field, before permanent deterioration.

Two effects dominate in damaging the electrodes and the insulators: the dark current and the power developed in a discharge. A reduction of the latter, as with the use of the 650 Ω resistance, helps in keeping the dark current to a low level, thus preventing damages to the deflector.

All the tests described have been carried out near the maximum attainable voltage, so it is not possible to foresee the long term reliability of the deflector when run at lower voltages. Tests in this direction will be done in the next months.

Acknowledgments

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References

1. E. Fabrici and A. Salomone, Proc. 9th Int. Cyclotron Conf., Caen (France) 1981, p. 501
2. C. De Martinis and D. Giove, Proc. 10th Int. Cyclotron Conf., East Lansing (USA) 1984, p. 575
3. M. Olivo, Proc. 7th Int. Cyclotron Conf., Zurich (Switzerland) 1975, p. 292
4. R.F. Holsinger and C. Iselin, The CERN-POISSON Program Package (POISCR), CERN-T604