HIGH VOLTAGE TESTS OF A PROTOTYPE ELECTROSTATIC DEFLECTOR FOR 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 goal is to withstand electric fields up to 140 kV/cm across a 8 mm gap,as required for the most energetic particles.

The results of the high voltage tests on the electrode support insulators and on a full scale prototype of the deflector are discussed. Preliminary results on the effects of the magnetic field on the voltage holdoff capability are also presented.

Introduction

The extraction scheme of the Milan Superconducting Cyclotron, as resulted from an extensive beam dynamics analysis (1), is constituted of two electrostatic deflectors placed in two successive hills, followed by a set of magnetic channels of passive type inside the vacuum chamber and throughout the yoke transversal. The requirements that the design of the electrostatic deflectors must fulfill can be summarized as follows:

- the maximum value of the electric field needed for the extraction of the most energetic particles is 140 kV/cm
- the very wide dynamic range of the Milan Cyclotron requires that the electrostatic deflectors can move radially over a 3 cm range
- due to the large differences in the scalloping of the extracted trajectories at the various field levels the deflectors have also to be adjustable in shape.

Therefore they have been designed splitted at least in two parts connected by a swivel joint,approximatively in the center of each deflector. The error in fitting the various trajectories is within 1.2 mm for the first deflector and 0.5 mm for the second one. In fig. 1 is shown the design of the first electrostatic deflector together with the actuators for the radial movement and the high voltage feedthrough.

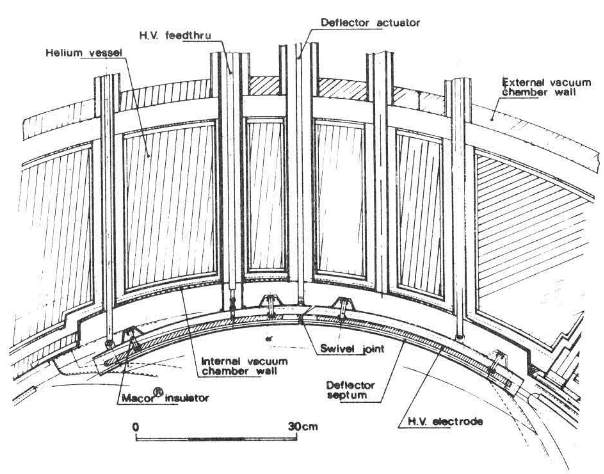

Fig. 1 - Design of the first electrostatic deflector

As dictated by the cyclotron geometry in the extraction region the deflector frame allows a vertical clearance of 54 mm and a radial one of 55 mm. The electrode septum gap is 8 mm wide in order to be compatible with the radial emittance of the various beams. In order to check the voltage holdoff capability of the deflectors a full scale prototype of the first one has been built. Preliminary tests have indicated that the insulators supporting the high voltage electrode are a critical component. Consequently extensive tests have been carried out on insulators alone in order to select the material and to optimize the insulator geometry. Then the full scale prototype of the deflector has been tested as a whole.

Experimental test set-up and procedure

The insulators and the electrode arrangements were tested in a vessel evacuated by a turbomolecular pumping unit down to a pressure of about 10^{-6} mbar. The direct voltage is supplied by a SAMES unit continuously variable in the range 0 to 150 kV. A current limiting resistor of 1 MΩ connects the HV circuit and the testing vessel. A sketch of the experimental set-up is shown in fig. 2.

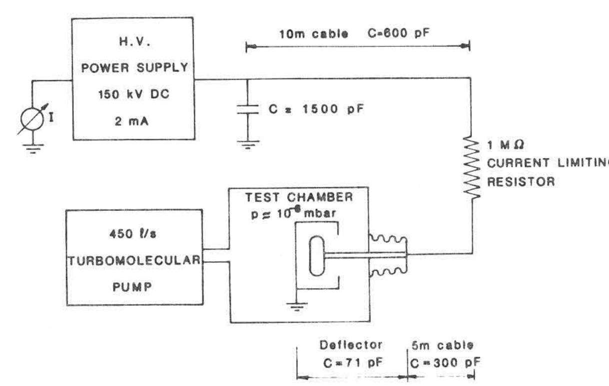

Fig. 2 -Schematic arrangement of the experimental test set-up

All components were ultrasonically cleaned in a detergent solution and rinsed with acetone and ethyl alcohol. The assembly is carried out using gloves in order to avoid organic contaminations. Thereafter the sample is placed in the vacuum chamber and allowed to outgass for at least 24 hours before applying high voltage. Current conditioning is routinely done by increasing the applied voltage in small discrete steps of 5 kV, and allowing the prebreakdown current to stabilize between successive increases. The emission current is monitored and a NaI scintillator with a thin beryllium window has been used for X-rays detection. The voltage holdoff capability is defined as the voltage which is maintained for at least 1 hour without flashover.

Insulators supporting the high voltage electrode

Insulators supporting the high voltage electrode in vacuum can substancially lower the electrical strength of the system. Extensive work carried out on the past ten years (2,3) has theoretically suggested and experimentally confirmed that high voltage applied to insulators results in an accumulation of positive charge on the solid through regenerative secondary electron emission. Positive charges are created by electron impact,being the secondary electron yield of the insulator surface greater than unity,for impinging electrons energies typically between 20 eV and 5 keV(4). As a consequence the cathode field at the interface between metal,vacuum and insulator (triple junction) is enhanced,thus increasing the emission of primary electrons from the triple junction. If equilibrium conditions are not established flashover results by ionization of the electron stimulated desorbed gas. In view of these considerations,efforts have been made to chose the best material and shape of the insulators as well as to solve the problem of their contact area with the electrodes. The experimental arrangement for testing the insulators has a geometry completely similar to that adopted in the deflector design. A cross section view of the deflector through the insulator region is shown in fig. 3.

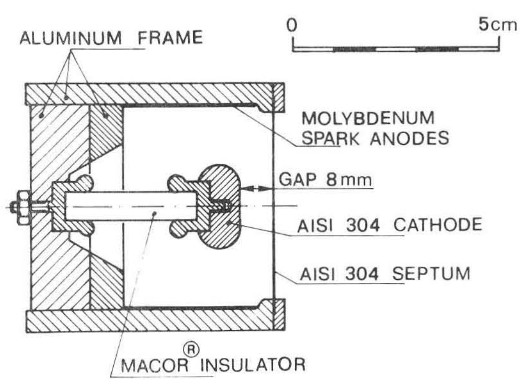

Fig. 3 -Cross sectional view of the deflector prototype. A similar geometry without the septum has been used to test the insulators

During the insulators tests the septum is not mounted . The insulators are 32 mm long and are fixed to a stainless steel support,through which they are screwed to the high voltage electrode and to the aluminum frame. Both ends of the insulators are placed into shallow recess in the supports, 5 mm deep. Therefore the interelectrode spacing is only 22 mm.The recess edges are terminated with a 2 mm radius. Insulators are fixed to the supports either by hot pressing or by bonding with Loctite. Results in the voltage holdoff capability are similar, but operation with the glue is resulted unreliable. In some cases,after a few discharges the insulators have shown a deterioration in the electrical strength, and successively they are found detached.

Three types of insulators material have so far been investigated: hot pressed Boron Nitride type HBC from Union Carbide, 92 % purity Aluminum Oxide produced by a national firm, and Macor ceramic glass by Dow Corning. Cylindrical rod insulators,7 mm in diameter,were preliminary tested. Boron Nitride and Macor specimens were machined on a lathe,while alumina was tested as received from the supplier. Voltage holdoff capabilities were not very different for the three types of materials ranging between 100 and 120 kV.

In some tests the end of the insulators have been metallized in order to eliminate the effects of voids between the insulator and the electrode. These voids could enhance the electric field in the vicinity of the triple junction, because of the difference in the dielectric constant between the vacuum andthe insulator. No relevant differences have been observed in the flashover voltage across metallized insulators as compared to the non metallized samples.The only relevant effect has been observed on alumina insulators. After a few sparks around 100 kV voltage,the voltage holdoff capability was decreased by more than 30 % in the non metallized samples. Examination of the insulators has shown evidence of flashover tracks on the dielectric surface starting at the cathode.

After these preliminary tests on different materials we have investigated the effect of the insulator shape on the flashover voltage. Tests have been performed only with Macor,which is a glass ceramic easily machinable with normal tools and shows better mechanical properties than Boron Nitride. Fig.4 outlines the various configurations which have been tested: conical shaped insulators with different vertex angles,cylindrical and grooved with two different diameters of 7 and 10 mm respectively.

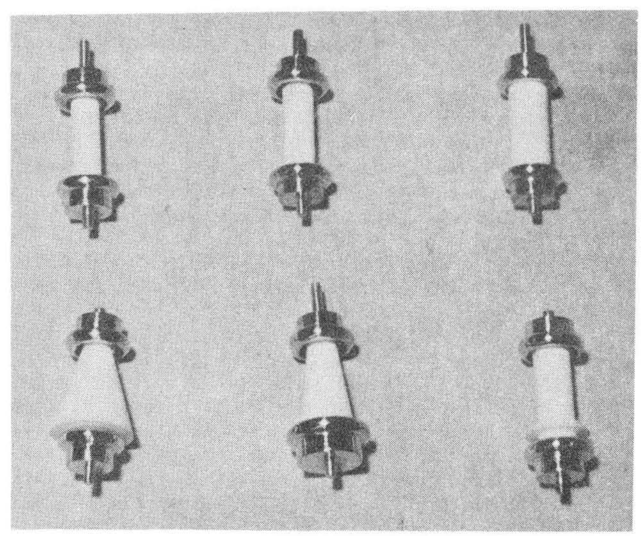

Fig. 4 -A view of the different shapes of Macor insulators tested. On the top, from left to right, 7 mm cylindrical geometry,M 7 and M 10 threated geometry. At the bottom conical shaped insulators

Results on voltage holdoff capability for these insulators are reported in fig. 5. Conical shaped insulators with their basis at the cathode have not shown improved electrical strength compared to the right cylinder. Results reported in the literature(5) show that a cone frustrum insulator, the lateral surface of which makes an angle with the field can result in a flashover voltage three times higher than a cylindrical insulator whose surface is parallell to the field. The optimum angle for higher flashover potential is reported to be around 30-50° and depends on the dielectric material. We think that a comparison with the reported values is somewhat difficult since the testing geometry in our case is very different from the standard one. The grooved insulator 10 mm in diameter proved to be the most successful one,holding voltages of up to 145 kV for more than one hour without flashover in repeated tests.

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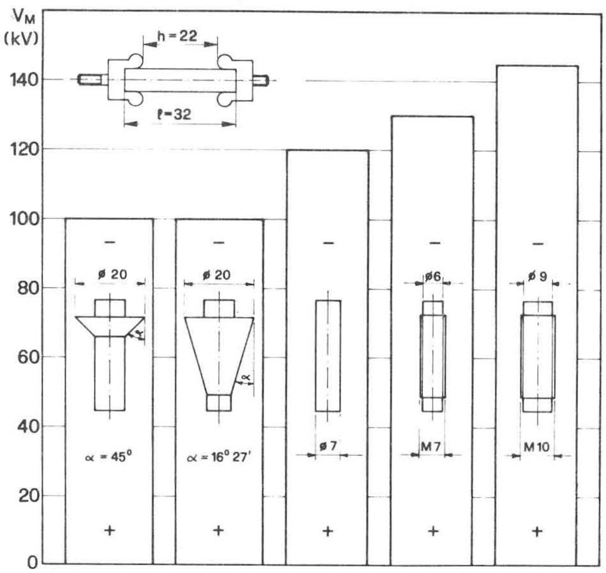

Fig. 5 -Voltage holdoff capability V_M for different shapes of Macor insulators

A remarkable point of this type of insulator is that high voltage can be held without problems just one day after they have been mounted in the test chamber, while it required several days conditioning to reach 120 kV with the cylindrical ones. A close view of this type of insulator is shown in fig. 6. The reason for testing such a geometry comes from the observation that insulator surface roughness affects the relative flash-over voltages. Rough surface gives a relative higher flashover value (6).

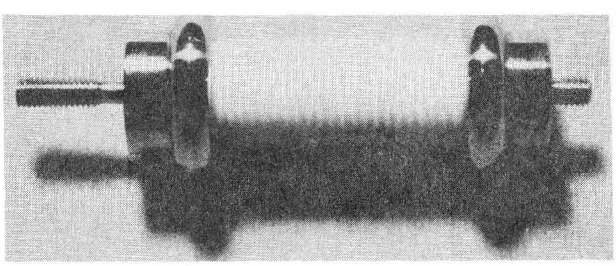

Fig. 6 -Close view of the M 10 threated Macor insulator

It is well known (7) that the breakdown voltage of a system decreases with the increase of the number of insulators. In order to the importance of the effect of the insulator number supporting the high voltage electrode of the deflector, 4 of the grooved type have been tested in parallell. We have not observed a great reduction in the flashover capability as they have sub-stained 135 kV for more than one hour without sparking.

Deflector prototype

A full scale prototype of the first deflector (the longest of the two), has been built in order to obtain data for the design of the final one. The main characteristics of the prototype are summarized in table I.

Both the high voltage electrode and the earth electrode are made of AISI 304 stainless steel. The entire deflector structure being attached to an aluminum frame. The high voltage electrode is 20 mm high and 10 mm large with the edges rounded with a 5mm radius to provide a smooth profile.

Table I
Main parameters of the electrostatic deflector prototype

Max. working voltage	112 kV
Gap	8 mm
Max. field strength	140 kV/cm
Length of the cathode	75 cm
Area of the cathode	192 cm^2
Cathode material	AISI 304 stainless steel
Anode material	AISI 304 stainless steel
Spark anodes	Molybdenum
Vertical spark gap	15 mm
Insulators	4,Macor(R) M 10 threated
Capacity	54 pF

The electrode is supported by 4 Macor insulators 10 mm in diameter, of the threated type, which have successfully withstand voltages up to 135 kV when tested alone. The test model deflector is shown in fig. 7. Half of the septum has been removed in order to visualize the high voltage electrode.

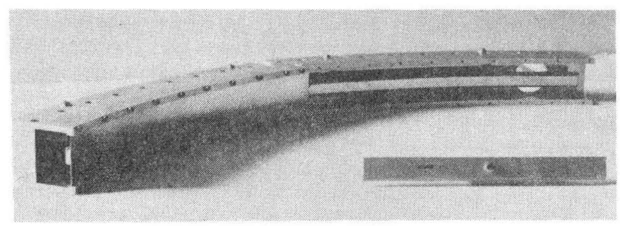

Fig. 7 -View of the electrostatic deflector prototype showing the stainless steel high voltage electrode and septum,and the aluminum frame

The radial profile of the electrode and of the aluminum frame have been machined with a numerical controlled milling machine, with an accuracy of 0.05 mm. The measured gap is within 0.1 mm of the design value of 8 mm. Molybdenum spark anodes (0.5 mm thick) are fixed above and below the high voltage electrode, the resultant spark gap being 15 mm. The aluminum frame and the cathode are splitted into two parts connected by a swivel joint which allows a rotation of 5°. This is made in order to change the shape of the deflector, thus properly fitting the trajectories of different beams. A close view of the deflector swivel joint is shown in fig. 8.

The prototype deflector has been tested in the test chamber. After a two days current conditioning the maximum voltage of 120 kV has been reached. This corresponds to an electric field of 150 kV/cm which is somewhat higher of the required operative value of 140kV/cm. Holdoff voltage in the range 110-120 kV are easily reproducible and the sparking rate is lower than 1 spark per hour, the dark current being of the order of few μA. Examination of the electrodes after extensive sparking has shown no evidence of macroscopic damages of the anodes. This could imply that the principal cause for breakdown events are cathode initiated phenomena. Further tests carried out with the septum disassembled did not improve the breakdown voltage of the system, some sparking occurring between the rounded edges of the high voltage electrode and the spark anodes. This shows that the electrode profiling adopted is not suitable and field computation will be done in the next future in order to define a better geometry of the electrode edges. Results so far obtained have shown that the electrostatic properties of the deflector are very close to that needed in operation,but the safety margin is still too low for day to day operation.

However the swivel joint has not proved to be a severe limitation in the design of the deflector.

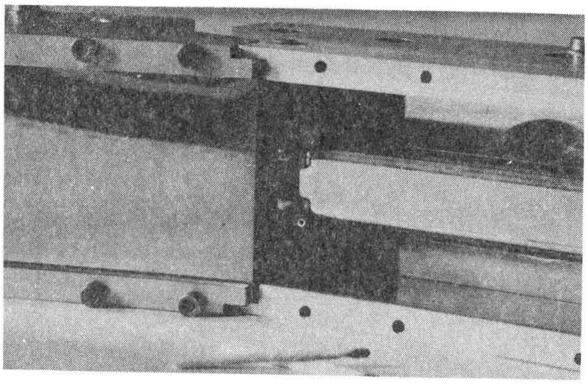

Fig. 8 -Close view of the electrostatic deflector showing the swivel joint

Preliminary tests with a magnetic field

Some preliminary tests have been carried out with the prototype deflector in the magnetic field of the 45 MeV proton Milan Cyclotron. While electrostatic properties are the same to those obtained in the test chamber , when a 10 kG magnetic field is applied,there is a decrease in the voltage holdoff capabilities of the system,sparking occurring at voltages around 90-100 kV. The reason for this is that electrons emitted from the cathode are focused in small spots,enhancing the power density hitting the anode,thus turning the cathode initiated breakdown to anode initiated breakdown. Neverthless the most catasthrofic effect is that after a few sparks have occurred,it becomes impossible to withstand voltages in excess of 70-80 kV. At 80 kV the dark current is around 250 μA, with an exceedingly high microdischarge rate. Inspection of the deflector has shown permanent damage to the molybdenum spark anodes and melted anode material was deposited on the high voltage electrode. This explains the reduced performances of the deflector following a discharge. The effect is rather independent from the magnetic field level having been observed with the same characteristics at field down to 3 kG. We deem that no substancial difference will arise from the high magnetic field (5 T) of the superconducting cyclotron. A few considerations related to the observed effects are exposed in the following, together with envisaged solutions whose validity will be checked in the next months.

- The reduced voltage holdoff capability is dependent from the field emission current by cathode microprotusions. We feel that it would be possible to decrease drastically the emission current with respect to the present situation,thus enhancing the insulation voltage of the gap. This can be obtained either by a better preparation and conditioning of the electrodes,or by choosing other materials for the high voltage electrode. Good improvements in the voltage holdoff capability are reported in the literature by using electropolished electrodes (8) or by dielectric coatings of the cathode. An increase of a factor of two in the electrical strength is reported by Rohrbach (9) for oxide coated aluminum electrodes,compared to AISI 304 stainless steel electrodes.
- The irreversible damage to the anode which results in a serious voltage limiting effect is related to the stored energy of the system which is developed during a spark. The energy can be limited and controlled by the series current limiting resistor,the 1 MΩ resistor resulting too low in our case. Successfull results are reported from SIN (10) with a 25 MΩ series resistor and with a 750 Ω resistor placed inside the high voltage feedthrough connector.

Conclusions

A prototype deflector for the extraction system of the Milan Superconducting Cyclotron has been extensively tested. From the results so far obtained the following conclusions are in order:

- the electrostatic properties of the deflector are quite close to those needed for the cyclotron operation. The grooved insulators,10 mm in diameter,have proved to work fairly good,withstanding voltages up to 145 kV without sparking. Also the swivel joint does not seem to represent a severe limitation to the deflector design
- preliminary tests in the presence of the magnetic field have shown two different phenomena:
  i)a reduced voltage holdoff capability around 90-100kV
  ii) after a few discharge a permanent damage to the spark anodes results in a more drastic reduction in the flashover voltage (70-80 kV).
- the analysis of the reasons of the reduced electrical strength of the deflector in the magnetic field and results reported in the literature have suggested that a more suitable preparation of the cathode and some changes in the high voltage supply circuit can help to overcome these difficulties.

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