THE ELECTROSTATIC DEFLECTORS FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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ABSTRACT

An extensive experimental program has been carried out at the University of Milan in the last years, to develop electrostatic deflectors which can comply with the performance requirements of the superconducting cyclotron, despite the reduced clearances. The results clearly enlightened that the presence of the magnetic field has a strong influence on the deflector performances, resulting both in a significant lowering of the maximum achievable voltage and in a strong enhancement of the damaging effects of discharges. The design of the electrostatic deflectors for the extraction of the beam from the Milan Superconducting Cyclotron has been completed, following the indications obtained from extensive tests carried out on different prototypes in a 1 T magnetic field.

In this paper we report the results obtained in the long term reliability tests of the deflector, together with the performances of a commercial high voltage cable used as the voltage feedthrough. An analysis of the modification induced in the electrical discharge by the presence of a high magnetic field. Moreover, the temperature enhancement of different materials used as liners is also presented.

INTRODUCTION

Two electrostatic deflectors are used for the extraction of the beam from the 5 T magnetic field of the Milan Superconducting Cyclotron.

The design of the extraction system has been described in details elsewhere[1]. Here we briefly recall the main features of the deflectors. Because of the compactness of the cyclotron geometry in the extraction region the vertical and radial clearances of the deflector housing are limited to 50 mm. They are split into two parts electrically connected to compensate the large difference in the scalloping of the extracted trajectories.

As reported at the Tokyo Conference[2] voltages of 105-110 kV were reached and held for at least one hour in a 1 T magnetic field, before permanent deterioration occurred. All these values are referred to the maximum attainable voltages, so that we had no indications on the long term behaviour of the deflector when run at lower voltages. Therefore an experimental program has been carried out in order to investigate the long term reliability of our prototype and to develop a satisfactory design of the swivel joint and of the high voltage feedtrough. Moreover, for a better understanding of the role of the magnetic field in limiting the maximum achievable voltage, a study of the trajectories of the field emitted electrons and of the temperature enhancement of the anode liners has been undertaken.

EXPERIMENTAL RESULTS WITH A 8 MM GAP

A picture of the deflector prototype used in the long term test is shown in fig 1. The overall geometry is similar to that adopted in the Cyclotron, except for the length which is reduced to 250 mm. The high voltage electrode is in titanium with a 5 mm radius rounded edges, and is supported by two Macor insulators. The septum is in tantalum, the liners are in molybdenum, and the housing in aluminium.

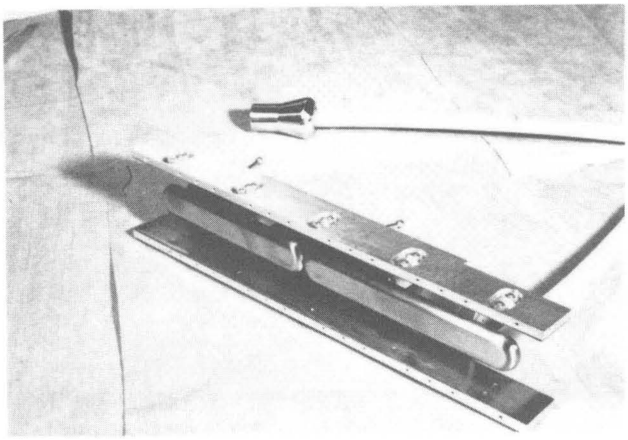

Fig. 1 A view of the deflector prototype. The HV cable used as the feedthrough is also shown.

The main difference with previous prototypes is in the swivel joint. The high voltage electrode is simply split into two parts which are electrically connected by a thin contact, held positioned by a spring into two holes in the electrodes, thus allowing the requested rotation.

The experimental set-up, the test chamber and electrode preparation and test procedure have been extensively described in ref.2.

The deflector is current conditioned without magnetic field up to 115-120 kV. The current is limited to 60 μA and the whole procedure takes about twelve hours with a final dark current which is typically of a few μA at 100 kV. Thereafter the voltage is lowered to 70 kV and the 1 T magnetic field is switched on.

The deflector is run continuously at the set voltage for at least one week and thereafter the voltage is increased in 5 kV steps. With this procedure the maximum voltage which has been held reliable in a time scale of weeks is 80 kV. A few discharge per hour can occur, but the dark current is always limited to 10-20 μA. Any attempt to raise the deflector voltage triggers after a few hours of operation a continuous arcing against the liners with an irreversible deterioration of the deflector. The surfaces of the anodes perpendicular to the magnetic field lines, after a relevant number of discharges, show a lot of pitting as in fig.2 and the support insulator are found strongly metallized by the evaporated material from the liners.

The results so far presented are the average of repeated tests.The time evolution of the permanent deterioration of the deflector can slightly change from one test to another,but there is a strong evidence that it is impossible to sustain safely a voltage above 80 kV for long periods. This voltage, with a 8 mm gap, corresponds to an operating maximum electric field of 100 kV/cm, which compared to the design value of 142 kV/cm, represents a severe limitation to the operating diagram of the cyclotron. There is a strong evidence that in a critical geometry like ours, the magnetic field play an important role in limiting the maximum attainable voltage. In the following the results of the analysis of the influence of the magnetic field on the electrical breakdown are shortly presented.

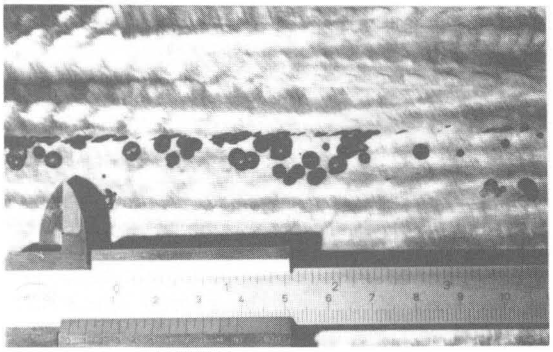

Fig. 2 Pits on a molybdenum liner after sparking at 85 kV in a 1 T magnetic field.

THE EFFECT OF THE MAGNETIC FIELD IN LOWERING THE VOLTAGE HOLD-OFF CAPABILITY OF THE DEFLECTORS

In order to have a better understanding of the effects of the magnetic field on HV insulation in vacuum, an extensive analysis of the field emitted electron trajectories and of the anode heating has been developed and applied to the geometry of our deflector[3]. We briefly recall the conclusions of this analysis. A numeric integration of the field emitted electron trajectories inside the deflector, strongly supports the evidence of a switching of the breakdown initiating process, from cathodic or micro-particle related phenomena to an anode vaporization induced by magnetically focused electrons. A few typical examples of such strongly focused electron envelopes are shown in fig 3.

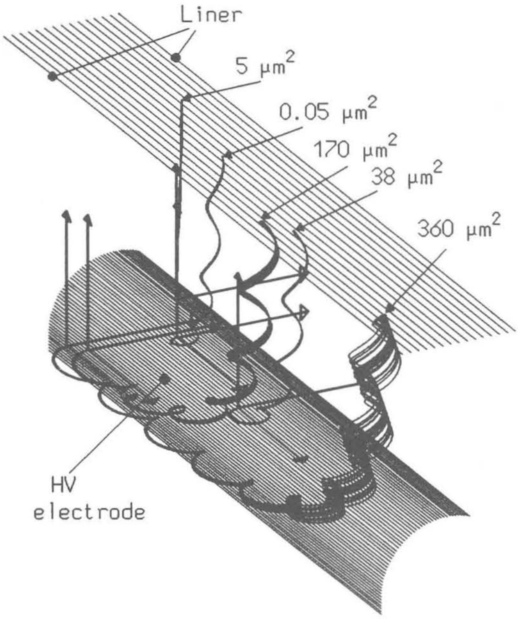

Fig. 3 Sketch of the electron trajectories for different locations of the emission site (B=1 T, V=100 kV).

Different locations of the emission site on the cathode have been considered and the relative impact area on the anodes are indicated. The shapes of the spots obtained fit rather well with the pits shown in fig. 2. The trajectory envelopes and consequently the impact surface are strongly dependent on the applied voltage, on the magnetic field and on the position of the emission site involved. However a few typical consideration can be drawn from these graphs. There is a different behaviour when the emitting site is located in the straight section of the HV electrode or near the beginning of the its curvature, with respect to locations closer to the electrode area facing the anode liners. In fact, in the first situation the drift motion due to the different orientation of the electric and the magnetic field lasts enough to produce dispersive effects, resulting in typical stretched spots on the anode liners. Spot areas are usually too large to produce a dangerous enhancement of the anode temperature as long as dark current intensities are less than a few tens of μA. Unfortunately, in the second situation, electron beam envelopes are much narrower and furthermore they show typical accumulation points; spot areas can be a few order of magnitude smaller than in the situation previously described. Following these considerations, an investigation of the thermal effect due to this focusing has been undertaken. Literature available formulas[4,5] are not suitable for our purposes since they do not consider the effectiveness of electron multiscattering in widening the energy distribution inside anode materials: such effects can not be neglected whenever spot dimensions become comparable with the lateral straggling of electrons. Moreover, the usual treatment does not take into account the temperature dependence of thermal conductivity and requires the knowledge of the so-called power retention factor, which is mainly related to back-scattered electrons; this factor is not generally available in literature for all material and electron energy.

Therefore a Monte Carlo simulation of the electron motion inside a few typical anode materials (tungsten, molybdenum and tantalum) have been performed using the EGS4 code, slightly modified for this task. The r,z energy distribution has been then converted into temperature distribution by numerically solving the POISSON equation with a non-costant thermal conductivity.

The maximum temperatures so obtained are presented in fig 4, for V = 100 kV and for an electron current of 30 μA. The curves computed with the formulas of ref. 4,5 are also shown, assuming an "effective" energy deposition depth equal to one half of the electron extrapolated range and a suitable average value for the thermal conductivity . The results behave as expected. For large values of the radius-to-depth ratio our data agree well with the usual ones, but as soon as the electron lateral straggling is no longer negligible, the temperature increases more and more slowly with decreasing radii, showing a saturation behaviour. The effect is more visible for Molybdenum since it is the lightest material considered.

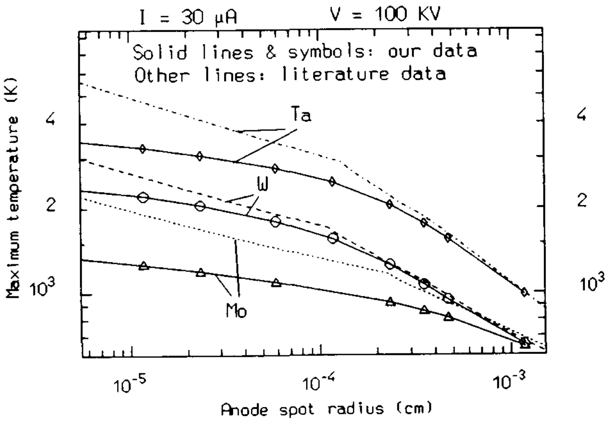

Fig. 4 Hot spot temperature as a function of the impact area.

Although the temperatures shown in fig. 4 for the smallest radii can be lower than the melting one, especially for Mo and W, they are likely to be high enough to trigger the discharging mechanism, via vaporization and/or a strong reduction of the thermal conductivity due to surface chemical changes. With the assumption that the ratio between the discharge "triggering" temperature and the melting one is roughly independent from the material, which is reasonable at least for vapour pressure related effects, it is possible to make a comparison among the materials considered. Tantalum clearly behaves worse than both tungsten and molybdenum. Molybdenum seems to be slightly better than tungsten, but similar data computed assuming a 100 μA electron current (typical for partially deteriorated electrodes) reverse this impression. Furthermore these data show that with 100 μA nearly every emission site can be critical in triggering the discharge. Moreover, with such a current intensity, actual melting of the anode can occur. In summary our analysis demonstrated that magnetic focusing of field emitted electrons is likely to be the key for explaining the lowering of the maximum sustainable voltage. However, as long as dark currents are reasonably low, only emitting sites located in a few positions on the electrode surface can actually trigger the discharge, as the most ones does not provide electron beams focused enough to significantly raise the anode temperature. The drastic deterioration of the apparatus performances which usually occurs after few discharges can be explained too, considering the effectiveness of the energy stored in the HV circuit and released during the discharge in strongly increasing the anode damaging. This effect too is enhanced by the focusing properties of the magnetic field. Therefore, if the stored energy is high enough, a partial deterioration of the electrodes takes place after few discharges (typically due to the dirtying effect of the anode melted material) and, as previously discussed, any emitting site becomes critical.

EXPERIMENTAL RESULTS WITH A 6 MM GAP

Following the analysis previously discussed, it is difficult to make any theoretical prediction on the voltage hold-off capability of the deflector, but a few general consideration can be drawn, which can help in overcoming the limit of 100 kV/cm, as resulted from the experimental test. We believe that two phenomena are mainly responsible for the lowering of the deflector performances in a magnetic field. They are respectively:

-the strong magnetic focusing of the dark current electrons,which trigger the discharge at a voltage value considerably lower (20-30%) than without magnetic field.

-the critical effect of the energy stored in the system and released during the discharge.The associated power density is strongly enhanced by the focusing effect of the magnetic field and beyond a given value becomes so catastrophic that the electrodes are permanently damaged.

A suggestion which can be drawn is that a reduction of the inter-electrode gap, resulting in a lower stored energy and in a lower electric field parallel to the magnetic one, for a given electric field in the gap, should enhance the capability of the deflector.
For a given electric field in the gap the stored energy is lower and the electric field enhancement along the HV electrode surface is reduced, particularly in the region facing the sparking liners (see figure 5). Even when working at the same voltage, the electric field in this critical area is not significantly higher, because mainly dominated by the vertical sparking gap.

It turns out that the maximum field in the critical region for sparking, in the 6 mm case is about a 30% lower, thus resulting in a lower dark current and in a more stable electrode. If we compare the behaviour of the electric field in the region facing the liners, for the same applied voltage, we find that the difference is not so large, because the dominating contribute is the distance from the liners, which is the same in both cases, and not the distance from the septum.

As far as the stored energy is concerned, this is not significantly enhanced by a reduction of the gap, when running at the same voltage, for two reasons:

-The stored energy has a quadratic dependence on the applied voltage against a linear one on the capacitance.

-the capacitance involved is not significantly increased, reducing the gap, as it is dominated by the capacity of the feedthrough.

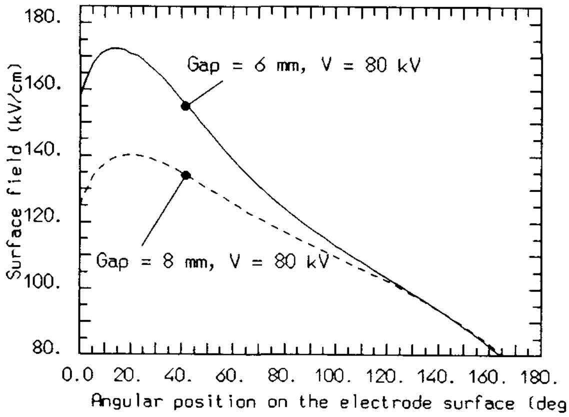

Fig. 5 HV electrode surface electric field as a function of the angular position (gap=6 and 8 mm)

As an example the energy stored in our prototype is nearly 0.4 J, both for the 8 and the 6 mm gap. These value is considerably lower than critical values (≈10 J) necessary for permanent damages of the electrodes when operating without magnetic field[4]. It turns out that a reduction of the gap, for a given applied voltage, increases linearly the electric field in the gap, without any appreciable variation in the stored energy and in the dark electron current heating effect.

This hypothesis has been experimentally tested running the deflector with the inter-electrode gap reduced to 6 mm. The test procedure was exactly the same as for the 8 mm gap and the results obtained look very promising. A voltage of 80 kV has been held for weeks without any critical sparking. This voltage for a 6 mm gap corresponds to an operating electric field of 133 kV/cm, which is very close to the project requirement.

HIGH VOLTAGE FEEDTHROUGH

The high voltage feedthrough is a critical component of the deflector, because the allowed room in crossing the cyclotron cryostat is limited to a 38 mm diameter tube. The use of a rigid coaxial conductor is rather difficult, because of the high electric field in the central conductor and of the mechanical problems also related to the translation and rotation of the deflectors.

For these reasons we have investigated the possibility of using as the feedthrough a commercial 150 kV cable with good results. The cable, which is shown in fig. 1, has a diameter of 12 mm and the ground shield has been removed. The cable insulator is threaded at the both ends and it is screwed into the electrodes. The system has proved to work reliably for an applied voltage up to 120 kV. Beyond this value sparking occurs and the insulator is permanently damaged. The cable behaviour is very satisfactory at voltages lower than 120 kV. The same cable has been used for months in all the tests reported in this paper. The only change that we have seen in the properties of the cable is an increased rigidity near the fixings to the cathode,and we believe that it results from the electron bombardment of the insulator.

CONCLUSIONS

The high performances required to our electrostatic deflectors proved to be difficult to meet, expecially on a long term basis. However, a careful analysis of the effect of the magnetic field has suggested that a gap reduction could result in a significant improvement. Experimental tests succeeded in confirming this prevision: voltages up to 80 kV corresponding to a gap field of 133 kV/cm have been successfully sustained for weeks. No significant difference in the performances is expected to derive from the 5 T field of the cyclotron, due to the saturation effect on the anode temperature previously described.

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