STATUS OF THE ELECTROSTATIC DEFLECTORS OF THE MSU K500 CYCLOTRON*

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The electrostatic deflectors of the MSU K500 superconducting cyclotron are currently limited to operation at voltages significantly lower than those required to extract full energy beams. We have constructed a test stand to determine the weak points of the design and to test proposed design changes. Results of tests of an improved insulator geometry are presented and plans for future tests are discussed.

Introduction

The MSU K500 superconducting cyclotron utilizes two electrostatic deflectors to extract the beam from the 5 T magnetic field. The design of the complete extraction system is described in detail by Fabrici, Johnson and Resmini[1]. The two deflectors, E1 and E2, have 7 mm gaps and must operate at 100 kV (140 kV/cm)

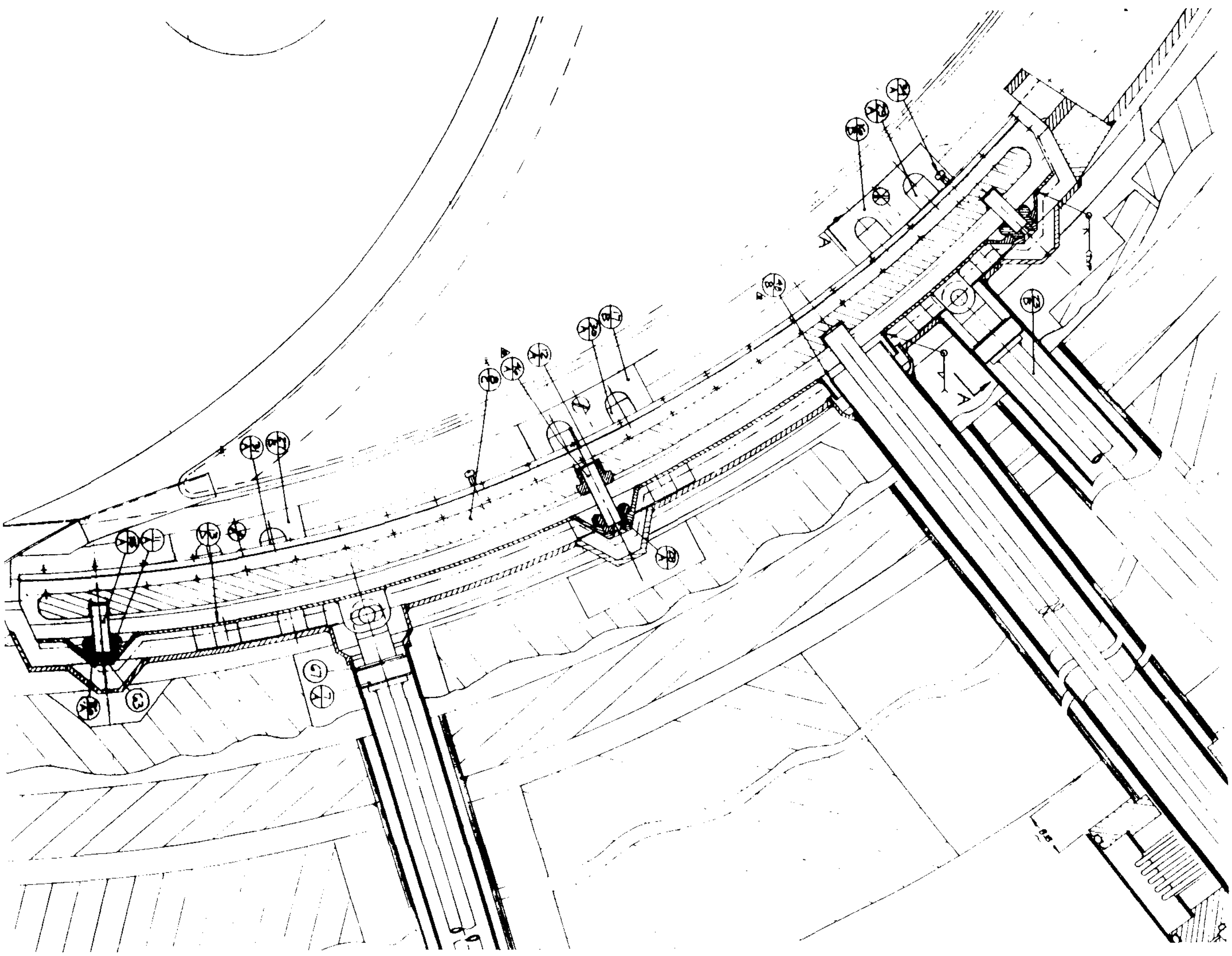

Fig. 1. A section of the K500 median plane showing the region around the second electrostatic deflector, E2.

to extract full energy beams. The corresponding VE number of 1.4 x 10^4 $(kV)^2$/cm is well within the limits established in previous cyclotrons such as discussed by Smith and Grunder[2]. However, the small size of our deflectors as required by the compactness of the superconducting cyclotron has led to voltage limitations as described below. These limitations currently permit the extraction of beams with energies of only 60 or 70% of the cyclotron design values in the stand-alone mode. As an injector for the K800 cyclotron the K500 will not require high voltages, but then the deflectors of the K800 may become a limitation. Hence, the results of present tests and developments are important for the final design of the K800 extraction system.

Deflector Parameters

The K500 deflectors are necessarily very compact because of the small magnet gap (50 mm) vertically and the proximity of the extracted orbit to the inner wall of the coil cryostat radially. The housing of E2 is slightly narrower radially than that of E1. A horizontal section of the cyclotron in the vicinity of E2 is shown in figure 1 and a photograph of the housing of E2 is shown in paper A3 of these proceedings. E1 is about 65 cm long and E2 is about 52 cm long. In both deflectors the gap is 7 mm. The cathodes or shoes are 12.5 mm thick and 25. mm tall with 12.5 mm diameter semicircular tops and bottoms and 12.5 mm tall flat surfaces on the fronts and backs. In each deflector the shoe is supported and held to the proper curvature by three insulators, the two end ones in compression and the center one in tension. The insulators are relatively short, 12 mm long in E2 and 16 mm in E1. The radial positions of both E1 and E2 can be varied remotely via push rods as indicated in figure 1. The high voltage is fed to the housings through a coaxial vacuum feedthrough as is also shown in figure 1. These feedthroughs penetrate the coil cryostat and are only 2.7 cm ID with 1.2 cm diameter high voltage center conductors. The deflector power supplies are high frequency Cockcroft-Walton types with very low stored energy and rated at 100 kV and 1 ma.

In the cyclotron currently E1 and E2 can be operated fairly routinely at about 60 and 40 kV, respectively. At voltages above these the performance is erratic and the deflectors are subject to insulator and/or high voltage feedthrough failure.

Deflector Test Stand

In order to test variations in the deflector design a test stand has been constructed. The test stand consists of a vacuum box with stainless steel sides and low carbon steel top and bottom constructed in the gap of a 10 kG magnet. The box is pumped with a turbomolecular pump and is a metal-sealed system. The high voltage feedthrough is the same as on the cyclotron with the additional option of a larger diameter tube. A second set of E1 and E2 deflectors has been constructed for use in the test stand. This set is interchangeable with the first set which makes it possible to pretest deflectors in the test stand and rapidly replace deflectors in the cyclotron when their performance deteriorates. When either E1 or E2 is being operated in the test stand the housings can be viewed from both ends through glass windows in the vacuum box. The viewing is usually done via television cameras because of the x-ray hazard through the glass windows. Sparks along the end insulators and shoe-to-sparking-plate sparks can be seen clearly. Sparks in the high voltage feedthrough tube or on the center insulator can not be seen. During long term runs in the test stand the power supply voltage is recorded on a strip chart recorder so that sparks are then visible as voltage fluctuations. The power supply has a maximum voltage of 150 kV and a maximum current output of 2 ma, but the current limit is usually set at 0.15 ma.

Insulator Developments

The insulators seem to be the weakest point of the original deflector design. These insulators were 7.7 mm diameter alumina rods with stainless steel corona ring end caps thermally fit onto one or both ends; only the anode end for the end (compressive) insulators and both ends for the center (tension) insulators. The details of these insulators and end caps are shown in reference 1, except that in that reference the end insulators are shown with corona rings on both ends.

The failures of these insulators were sometimes electrical and sometimes mechanical. The mechanical failures were often fractures at the stress points caused by the thermally fit end caps. The electrical failures were sometimes caused by sparks through the interior of the alumina, mostly in the compressive insulators at the tips without end caps. Metalizing these tips to eliminate the strong fields between these tips and the cathode did not cure this problem. Interior sparks were also sometimes initiated through the sides of the compressive insulators near the edge of the hole in the cathode into which the tips were recessed. We tried several sources and several grades of alumina, but found none which were completely immune to this problem. We were able to induce this type of failure (internal sparks) in a small insulator test stand without the presence of magnetic field. In individual insulator tests (without magnetic field) the insulators with corona rings on both ends almost always held 100 kV. They would reach 100 kV with very little conditioning required, typically less than 1 hour from pump down. On the other hand, of the insulators tested with the bare tip recessed into a 6 mm deep hole in the cathode, less than half of them survived to 100 kV without internal spark-induced fractures.

The mode of electrical failure of the insulators with corona rings on both ends is qualitatively different. With these insulators the deterioration was gradual and was associated with surface metalization and/or tracking. It was greatly enhanced by operation in magnetic field. With magnetic field the metalization is often in the form of dark spots on the alumina near the corona ring at the anode end. The insulators also get metalized with irregular tracks or plumes along their length.

We performed electrostatic calculations in order to understand these empirical results. These calculations showed a large field enhancement at the surface of the corona ring end caps and that this field points from the end cap towards the side of the insulator. It is apparent that large leakage currents can be produced by field emission from the corona rings and that electron bombardment of the anode end corona rings could cause evaporation of stainless steel onto the nearby alumina. The magnetic field tends to localize and enhance the damage. The tracks and spots tend to be concentrated on one side of the insulators as determined by the electron motion in the magnetic field.

Further calculations indicated that the ideal geometry for the insulators may be what we now refer to as the "plane geometry": cylindrical insulator butted flush to the plane surfaces of the anode and cathode. In searching the literature the only devices

CH1996-3/84/0000-0572 $1.00 © 1984 IEEE

we have found which use such a geometry are the large DC electrostatic particle separators at KEK in Japan[3].

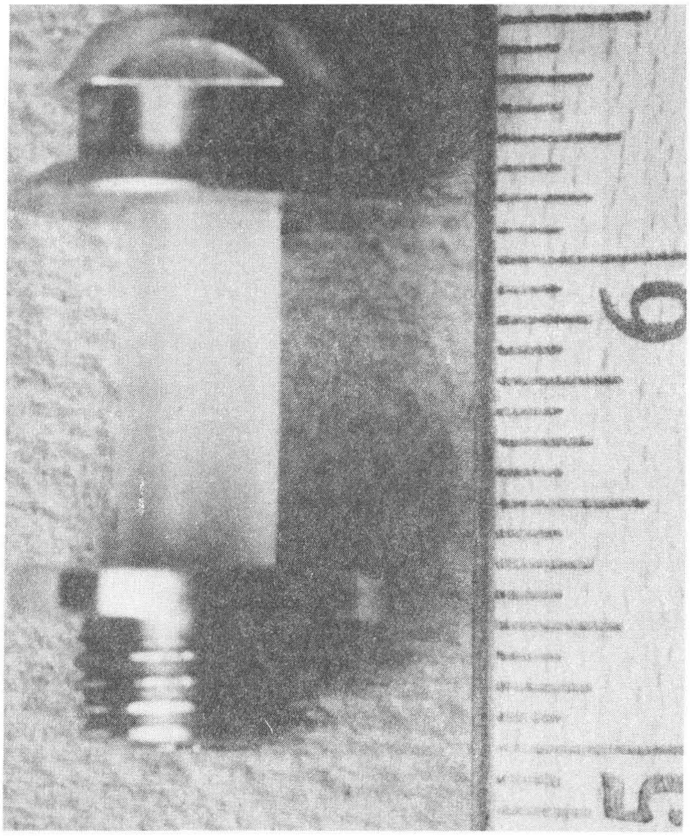

Fig. 2. A photograph of the new plane geometry insulator: sapphire rod soldered to copper buttons and stainless steel end caps. This is the center insulator (tension) for E1. The copper ends are recessed into the end caps. The scale is in inches.

We have made some new insulators in this plane geometry to fit the existing deflector housings and two of these are shown in figures 2 and 3. The mechanical bonds are made by soft soldering copper buttons to the ends of sapphire rods. The sapphire tips are first metalized with silver-based metalizing ink. We are currently setting up to hard solder these insulators, but all tests to date with this new geometry have been done with the soft solder bonds. The copper tips recess into close-fitting stainless steel end caps to form the plane interface at the ends of the insulators. At the shoe end of the compressive insulators the copper tip is 6 mm long and fits into the 6 mm deep hole in the shoe so that the end of the insulator is flush with the surface of the shoe. We are continuing to use sapphire because the solder joints are reliable and the material is of uniformly high quality. The costs of sapphire insulators ground to our specification are about $30.00 each[4].

The early tests of the new geometry insulators have been very encouraging. They have been tested in the E1 housing with the larger than normal diameter high voltage feedthrough tube in order to decouple the insulator tests from feedthrough problems. Initially the deflector conditioned up to about 80 kV and then high leakage currents developed. On inspection the insulators were coated, probably due to migration of exposed soft solder. The insulators were cleaned with an aluminum oxide sandblaster and reused. The second cycle through the test stand was similar to the first,

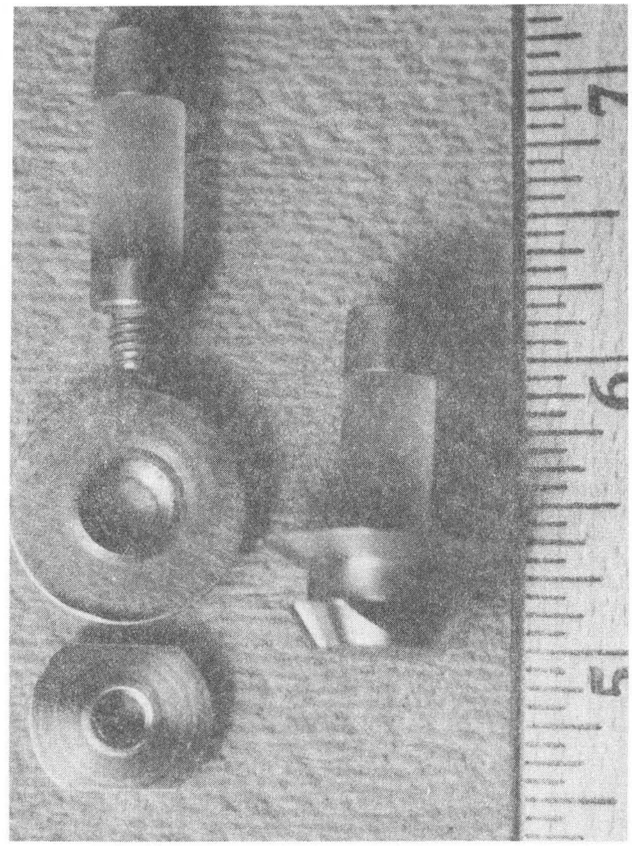

Fig. 3. A photograph similar to figure 2, except of of the new end insulators (compression) for E2. Two insulators are shown, one disassembled to show the separate pieces.

but on the third cycle the E1 conditioned to 105 kV and ran at that voltage for five days. At this voltage there were sparks external to the vacuum box related to the cages around the power supply and high voltage terminal on the test stand. Since then we have rebuilt the external high voltage shields, but have not repeated the tests of E1. E2 has been tested with smaller versions of these insulators and the standard diameter high voltage feedthrough tube. It has been run successfully for days at 65-70 kV where the feedthrough is the limit. For both deflectors the steady state dark currents were low, about 10 μa.

Other Developments

In addition to the plane geometry insulators some other small changes in the deflectors have been made. For example, the new E1 and E2 have been constructed with titanium shoes rather than stainless steel. Reference 3 indicated that in large gap separators Ti cathodes held about 20% more voltage than stainless steel. It is not clear whether the Ti shoes are actually better in our deflectors or not because the proper controlled tests have not yet been run. The 105 kV run with E1 was done both with the Ti shoe and the new insulators. Secondary benefits of the Ti shoes are that they are lighter than stainless steel by about a factor of 2 and the modulus of Ti is about half that of stainless steel, both factors tending to put less mechanical stress on the insulators. We have also tried Ti tubes for the center conductors of the high voltage coaxial feedthroughs for similar reasons. In this case the low modulus is detrimental because it allows larger electrostatic deflections of this conductor and results in mechanical vibration following sparks. A thin-walled Ti tube with a core of a high modulus light-weight material such as alumina or glass may be better. The field at the surface of this center conductor would be 180 kV/cm when the field in the 7 mm deflector gap is 140 kV/cm so this feedthrough must be treated with great care.

Jack Riedel has suggested a possible improvement for the high voltage feedthrough which involves replacing the center rod or tube with a metalized alumina cylinder. We have purchased these tubes, but have not yet designed the end pieces necessary to connect them to the shoe on one end and the high voltage terminal on the other.

A completely different idea for improving the feedthrough is to introduce an intermediate diameter tube between the inner and outer conductors floated at an intermediate voltage such as 50 kV with an independent power supply. This would significantly reduce the surface field at the inner conductor by increasing the field at larger radii, and it would also reduce the electron energy and the corresponding damages during sparks. (There would be two regions with small VE parameters, rather one with a large VE parameter.) One or both of these methods will be tried in the near future.

One last area which is currently being worked on is determining the optimum profile of the cathode shoe. Calculations show that the present shape, a 12.5 mm tall flat vertical surface with 12.5 mm diameter semicircles on top and bottom, produces a peak field of 180 kV/cm at the transition between the straight and curved sections when the nominal field in the gap is 140 kV/cm. Preliminary calculations using a shorter flat section and a more gradual transition to decreasing radius of curvature have reduced the peak field to about 150 kV/cm and have at the same time not seriously reduced the electric field uniformity on the median plane in the deflector gap. This shoe is, however, slightly thicker reducing the gap behind the shoe and the corresponding space for the insulators. With the plane geometry insulators this may be acceptable and we may have one of these new shoes fabricated on a numerically controlled milling machine.

References

* Supported by NSF under Grant No. PHY-83-12245.

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