DEFLECTOR DEVELOPMENT FOR THE K1200 CYCLOTRON

Thomas Kuo* and Jerry Nolen†

National Superconducting Cyclotron Laboratory

Michigan State University

East Lansing, Michigan 48824, USA

ABSTRACT

Certain progress has been made for the electrostatic deflectors of the K1200 cyclotron. At present, 80 kV at subμA leakage current can be achieved. The system has been operated in a stable, very few sparks and almost zero current mode for about a year and a half. The progress is attributed to a better understanding of various discharge phenomena at high magnetic field and the treatments to eliminate them. The future plan is to further improve the voltage holding capability to 100 kV, so that 80 kV would be obtained routinely and reliably.

1. INTRODUCTION

The voltage holding capability of the electrostatic deflectors had been one of the limiting factors of extracting higher energy beams. For K1200, the field strength required for the extraction of the 200 MeV/n, q/A=0.5 ions and the 135 MeV/n, q/A=0.33 ions is about 140 kV/cm (84kV at 6mm). The early performance of two deflectors used for K1200 was not able to meet this requirement. About two and half years ago, highest priority was set for improving these deflectors to acquire the capability of this field strength reliably thus to remove the limitation on extractable beam energy.

Progress has been gradual in small steps but in pace with the demands of beam requirement. At present, 80 kV with subμA leakage current is reachable. Below 60 kV, the deflector operation has been very stable,very few sparks with very low leakage. Breakdown occurance and unscheduled repair has also been down to minimal. This progress was possible mainly due to a better understanding on the high voltage discharge mechanisms in the deflector of a particular design. Some hardware improvement was important at the begining but became less critical later on as our techniques of handling discharges are better developed.

In the following sections, various discharge modes and the corresponding techniques of treatment are described. Future development to further improve the voltage holding capability to 100 kV and to handle high external beam operation for secondary/radioactive beams production is also proposed.

*present address: TRIUMF.

†present address: ATLAS, Argonne National Lab.

2. DISCHAGRE MECHANISMS

The origins and the characteristics of the discharges come from several subsystems in different modes. In terms of hardware the deflector system can be divided into three subsystems, namely:

—HV power supply and feedthrough,
—Supporting insulators and mountings and
—HV electrode and anode plates structure.

During our development, these three subsystems were studied and improved in the above listing sequence. In terms of the nature of discharges, they can be classified into two basic classes. The first is the random,short burst modes and the second the CW discharge modes. It turns out that the random modes are easier to be recognized and therefore easier to handle, but the CW modes are much more subtle thus the solutions to eliminate them are more elaborate. The following sections will discuss these individual modes in some details.

2.1. Random Discharges

Microscopic emissions It has been theorized that under high negative bias an electrode with macroscopic smooth surface will undergo micro-explosion[1)] due to defects or fornign materials in submicron sites where the local polarizing field is so strong that the material around these sites are exploded away. These micro-explosions continue until the sites of defect is exhausted under a given bias. A new series of explosions will be initiated when the bias is raised to a higher level.

Microscopic protrusions are also formed under high electric field resulting field emissions. The initial electrons collide with residue gas molecules and bombard the anode surface. Ions from the residue gas and from the contaminations on the anode surface are drawn back to the cathode releasing secondary electrons. If the magnetic field is very strong, say 5T, these ions will be concentrated onto the original emission sites, triggering intense secondary electrons and in turn intense ion emissions. This process eventually leads to a plasma discarge. A weaker magnetic field will allow this process to develop slower and to have higher possibility to melt off the protrusion. The behavor of this process is recognizable by its gradual current buildup prior to a spark or a gradual current decrament.[2)]

If the bias voltage increases slowly and constraint of current flow is added, these micro-explosions and micro-protrusion emissions would not be too harmful. In fact, one wants to control these discharges at a rate that conditioning to a higher voltage can be done without damage by heavy discharges. However, if the bias voltage increases in big steps, avalanching sequence of microdischarge would occur and major discharge events are triggered. Although deflector is considered a DC device, it acts like an unmatched transmission line during discharge. Standing wave of high currents up to thousands of amperes in amplitude rings back and forth. Many major discharges will follow if the oscillation are not heavily damped.

Gas emission discharges Gas desorption from the metal lattice of the cathode also contributes to random discharges while the gas released from the anode surrounding seems to be less eventful. It is inferred that when a burst of gas is released from the negative electrode, a glow discharge is formed which further induces more gas release. These mini glow discharges have been observed through a window of a test facility. A very clean observation was obtained as follow. A cathode coated with non-absorptive glass was cycled with pressurization and evacuation after the typical conditioning had been carried out. Usually no recondition was needed to resume the voltage holding capability already reached. On the other hand, another cathode coated with Alumina layer (slightly porous) needed to be reconditioned for every cycle.

Macroscopic defects Random discharges stemed from macroscopic defects usually identify themselves by major discharge intensity and light emitting events. For K1200 deflectors, we have encountered defects coming from many sources. Examples are:

- material defects in supporting insulators.
- defects in component fabrication, system assembly.
- deterioration of negative electrode surface smoothness.
- deterioration and damage on anode surface.
- local sharp edges.
- non-conductive dust particles or fibers attracted to the cathode.

Some items also cause discharges in CW mode while those defects contribute to CW mode only are omitted here.

Discharges induced by dynamic EM fields It has been observed that violent discharges occur in the deflector during RF sparking when the deflector is set at a voltage beyond which it has not yet been conditioned to. In other words, the deflector is unstable in this condition. Similar effect takes place when the magnetic field is ramping up or down. One inferred that the RF penetrated into the deflector induces an RF voltage superimposed on the DC voltage. Likewise the change of magnetic field induced an EMF voltage. In both cases,the resulting field is higher than the level the deflector has attained, consequently discharges are triggerd. After repeated confirmation of this phenomenum the simultaneous conditioning of RF and deflector has been avoided. It is also manditory that when the deflector is being conditioned, ramping up/down magnet or bring up RF are excluded.

2.2. CW Discharges

The CW discharges (CWD) distinguish themselves from the random discharges by the continual current drainage. Currents start at a takeoff voltage then rise very rapidly with respect to voltage increase. Typical events are from defects such as whiskers developed on the cathode or from damage (craters and ridges) on the anode plates. There are situations in which several CWD start from different sites but at different takeoff voltages and they might superimpose with several types of random discharges. So the circumstance might be quite complex. Not all CWD are the consequence of the uncontrolled random events. For example, metallic chips might migrate to the vicinity of the cathode and eventually be attracted to the cathode surface. Once this happens, the performance of the deflector will be severely hampered.

Defects listed in the random discharge section are also sources of CWD. In addition to macroscopic defects, a few other discharge mechanisms exist even if the deflector is in its *perfect mechanical* condition. They are called Reverse Penning, ExB and Thermal field emission modes.

Reverse Penning mode This CW mode occurs as a consequence of a twofold symmetric electrical geometry imerged in a strong magnetic field perpendicular to the axis of the symmetry. The discharge is entirely symmetric from the negative electrode to the upper and lower anode plates up to very minor detail, as shown in Fig. 1. This mode take place most frequently at the locations where the highest electric field exists, e.g. the semicircle edge of the endtips of the electrode at the median plane. The process ignites like an arc formation and once it has started the 'arc' current could be up to a few hundred microamps. The arc is able to self sustain even if the current is limited to 10 μA. We found that this discharge is most destructive and it is necessary to turn off the high voltage to extinguish it. Due to limitation of space, we shall offer the explanation in a separate publication.

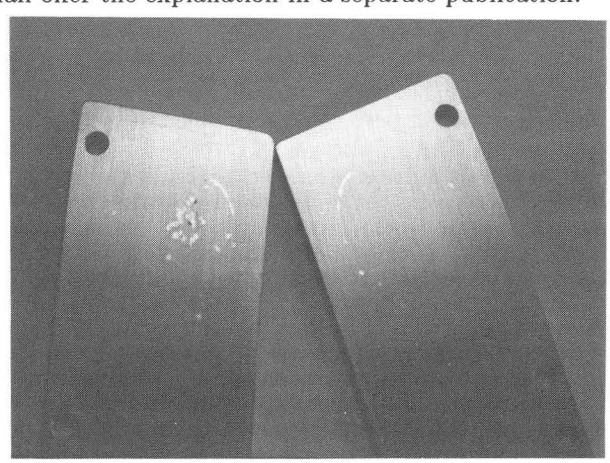

Fig. 1. The etching on the upper and lower sparking plates by CW reverse Penning mode. Note the complete symmetry of the crescent shape.

ExB mode Fig. 2 shows an image of ExB discharge. The electric field is 140 kV/cm at 100 kV and the magnetic field is about 1T. The plane of moment of the intense electron core lies in the deflector median plane but the pattern was captured symmetrically on both the upper and lower anode plates. The carbon tracks were produced by the hydrocarbon particles ionized by the ExB electrons. The electric and magnetic field made them record the image of the electron paths on the anode plates.

Electrons are initiated from a site (see the fine line of the first half circle and the sharp begining point) and contained by the magnetic field. Upon returning to the electrode the electrons are repelled again. Positive ions produced very close to the electrode and also energetic enough are pulled onto the electrode, otherwise they are pulled to the anodes. The secondary electrons follow the trace of the primary ones and this process continues until a spark is triggered. Many isolated tracks were observed indicating that this process is common. ExB electrons are very destructive to the supporting insulators located at the median plane particularly at the metal-insulator interface.

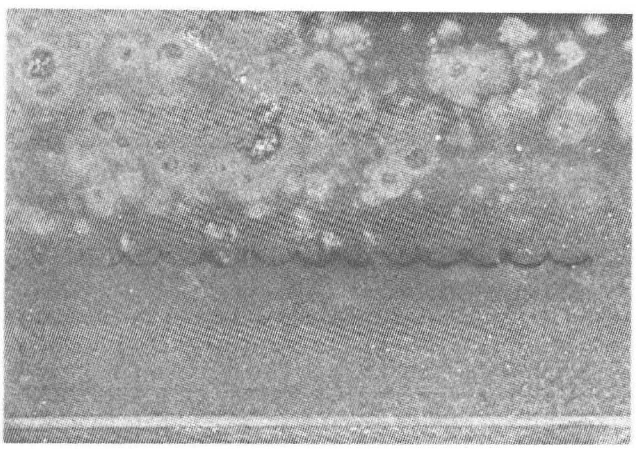

Fig. 2. Image of ExB electrons. note the spark damage from random discharge mode.

Thermal field emissions Operation experience shows that the E1 deflector with bare electrodes (vs. coated) performed perfectly at the begining of extracting about half μA of Oxygen $_{18}O^{6+}$ at 80 MeV/n, but started to draw current after two hours. If special attention were not given, the deflector currents might grow to an unacceptable level. The leakage decreased slowly after the beams was turned off. The time interval between beam on and leakage starting depends on how long the beams has been off, how high the beam currents and how the cyclotron is tuned. Subsequent inspection on the deflector indicated that the current flow was in the form of thin but long electron sheet along the front surface of the electrode. The etching on the anode plates was very narrow (0.2mm) but very long (about 30 cm), symmetric on upper and lower plates. Before the cooling for the deflector system is added, a set of coated electrodes was used. The symptom of this thermal field emission was much improved, but how high can a beam current be extracted remained unanswered.

3. HARDWARE IMPROVEMENT

In the previous section, we concentrated on the description of various discharge mechanisms but deferred the corresponding treatemnts for the sake of continuity and clearity. One might wonder that if that many discharge modes are recognized, the deflector problems would have already been half solved. This indeed is the case. Almost all of these discharges have been handled either by complete elimination or by minimization to a great degree (see Fig. 3. next page). The HV feedthrough and the supporting insulators were studied and improved first, then the anode plates and the negative electrodes. Basically, the development for the one-segment E2 is completed as far as the 80 kV capability is concerned. The three-segment E1 is more involved due to its complex mechanical structure.

3.1. High Voltage Feedthrough

The version of HV feedthrough used for the K500[3)] superconducting cyclotron consists of a long metal rod mounted coaxially with a 5 cm diameter spark tube. The rod is terminated by a large corona ring which is isolated from ground by a quartz tube. Sparks between the center rod and the spark tube had been a problem. A new design adapted by the K1200 replaced the vacuum coaxial line by a solid coaxial cable at atmospheric pressure. Fig. 4 shows the schematic of this design. The HV cable connects directly to the HV power supply and to the tip of the feedthrough which is latched into a hinge in the negative electrode. The HV tip and the ground tube are separated by a 15 cm long macor tube. The tip is made of Titanium and is brazed onto the macor tube by glass bonding. This bonding technique is developed at NSCL and is considered necessary because any metallic bonding would create macroscopic sharp points. The ground end of the macor tube is tapered so that the ground surface is gradually flared away to avoid abrupt field change at the cable-macor-ground tube interface.

The center conductor of the HV cable is removed as suggested by Bob Roger of Texas A & M University Cyclotron Institute.[4)] The remaining carbon rubber layer provides about 6 kΩ/in resistivity so a cable of 10 feet has a resistance of 720 kΩ. The resistive cable reduces the spark damage but additional resistance, in the order of 50 MΩ made by a string of resistors, is found needed to make the sparks non-destructive. However, this series limiting resistance can not stop the damage by the CW mode discharges. In the event that the leakage currents exceed 10 μA during routine operation, the 50 MΩ string can be replaced with a 5 MΩ string in order to reduce the voltage fluctuation.

Besides being used as HV feeding, the feedthrough is also used for deflector position drive. After 4 years of operation, our experience with this type of feedthrough has been very satisfactory. No HV or mechanical difficulty was encountered.

3.2. Supporting Insulators

The original sapphire insulators[3)] are being phased out for the reason that some of them glow to cherry red at 50-60 kV with large leakage currents. This is consistant with the observation that some insulators were found coated with thin metallic film at the HV end and high temperature colorations were printed on the anode plates. The brazing joint was found depleted due to the evaporation of brazing compound from high temperature. The metallic coating and the imperfection in fabrication of seating contributed to frequent flashovers. In other words, there existed volume defect, surface defect and sharp point defect associated with the use of the sapphire insulators. Before the new version of insulator was developed, only those which could sustain 80kV without glowing were selected. In the meantime, the problem of sharp point defect was corrected as much as possible (It could not be corrected completely because the original design called for sharp 90 degree fabrication).

Several versions of insulator made of Macor were developed. Macor is chosen for its machinability to achieve complex configuration, particularly for making ExB electron barrier. Sharp edge design was removed and the metallic brazing was replaced by glass bonding. One version increased the insulator cross-section about 50 % and the binding area to the cathode 150 % for stronger mechanical strength. All versions have been tested and used in the K1200 cyclotron. Their performance has been very satisfactory.

3.3. Cathode Electrode and Anode Plates

We have isolated the deflector system in three parts and studied them in operational sequence. With the first two parts free of discharges and difficulties we were able to concentrate on the deflector channel where the cathode electrode and the anode plates interact under the influence of a strong magnetic field. As we shall see later the effort to minimize the spark frequency and spark damage leads to the complete elimination of sparks on the anode plates which in turn leads to the complete suppression of the CW Penning mode and ExB mode. The thermal field emission is greatly reduced but not completely suppressed yet since the development of cooling capability has just begun.

Conditioning technique   Spark cleaning has been the conventional or usual method of voltage conditioning. The voltage holding capability is the prime object while the current drainage is considered secondary. In the situation of K1200, a moderate spark strength or a small current drain results in high power density on the anode plates because of the high magnetic field. Damage may develop very rapidly leading to a failure at low operating voltage.[5)]

A new technique for conditioning was then developed in order to minimize the spark damage. At first we added large series limiting resistors in the HV feedthrough to damp the high current ringings during a spark and clamp the maximum macroscopic pulsed currents under 20 μA. The characteristics of leakage currents or spark currents were monitored vs. time with resolution better than 0.2 second using a program called Fmon. The voltage is to increase in very small and gentle steps to smooth the micro defects. Each step begins with zero current, stops once a small current is seen. Several seconds to several minutes may be needed to bleed out the micro-emissions, mostly from gas desorption at lower voltage. At higher voltage pulsed discharges from a few μA to 10 μA (electronically clamped) followed by a continual bleeding are seen. If no CW mode discharge is initiated, currents will fall back to zero for each step.

The steps are in a few hundred volts incrament at lower voltage decreasing to 10 to 20 volts per step at the higher end. This procedure repeats for three cycles. The first is with the magnet current off (some residue field exists in the location of the deflectors). This cycle is used to clean the cathode (sites of micro-explosion, field protrusions and gas desorption), usually takes about 4-6 hours to reach 60 kV for a bare electrode and about an hour for a coated one. The second is with magnetic field at about 1 to 2 tesla to clean the anode plates and to melt off residue field protrusion and gas desorption sites. The third cycle is for final conditioning at full operating field. Using this procedure, we usually obtain conditioning without the high risk of damaging the deflector. This is demonstrated in Fig. 3.

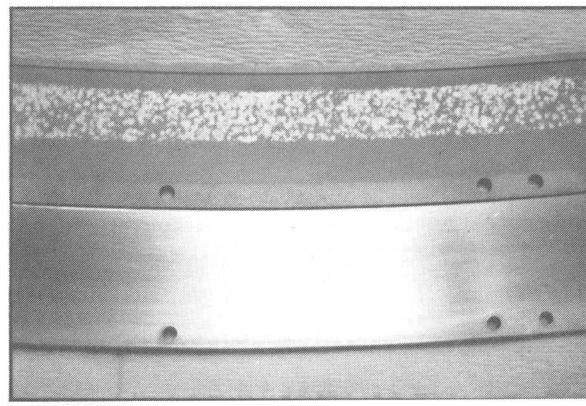

Fig. 3. The contrast of sparking condition between using the new technique (lower) to the traditional method (upper).

Anode sparking plates   reflectory metals such as Tungsten have been used for sparking plates for many deflector designs. One must emphysize that the tungsten plates must be of high purity and of high performance grade. The lower grade made by powder metallurogy will not work well because of its high impurity contents which contribute to the endless emission of ions of contamination. In addition, droplets of tungsten are sputtered off easily by the spark energy. These droplets are ionized and are attracted to the negative electrode. This action deteriorates the smoothness of the negative electrode hence triggers more sparks.

Lower melting point alloy with strong modular strength such as stainless steel might be useful as sparking plate material. At NSCL we have explored the use of s.s. as an option over the high grade tungsten for its ease in fabrication and the simpler construction it allows. Sparking tests show that the s.s. evaporates in the form of metal gas and coats the negative electrode evenly when a major spark occurs. The craters created by the sparks show smoothier boundary edges. Encouraged by this result the material was then used to make sparking plates for the E2 deflector. As a result, the negative electrode has maintained its smoothness ever since. Later on, the new conditioning technique and the use of electropolished s.s. anode plates made the complete elimination of random discharges possible.

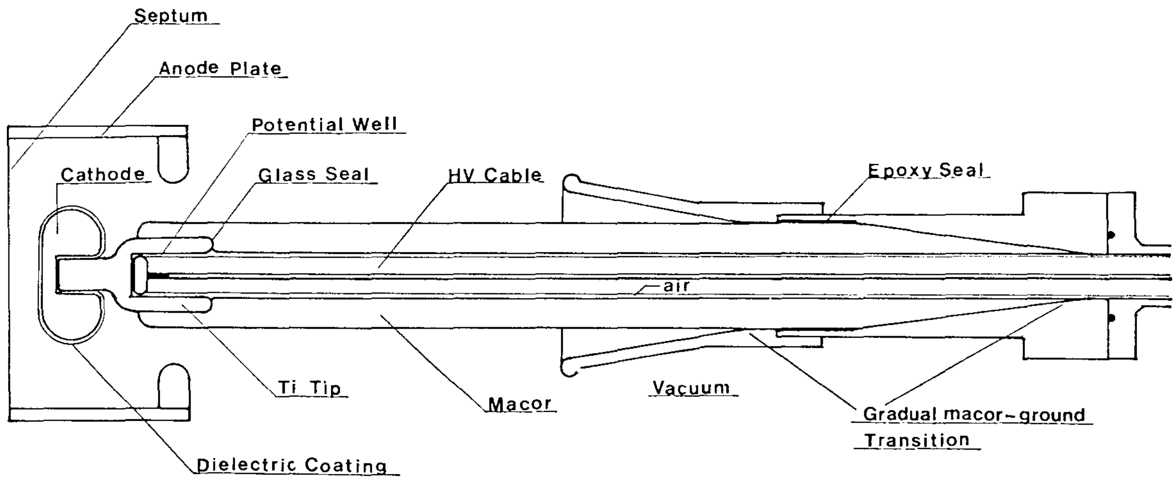

Fig. 4. The deflector channel structure and the main features of the new feedthrough design. Note the cathode is wrapped around cpmpletely by a layer of dielectric coating.

The ChalkRiver group also explored s.s., Ti and Mo as alternative anode material. Their conclusion is that Ti is the best when tested in a teststand.[6)] Further development at NSCL indicated that although s.s. works well in handling the random discharges, but on the other hand is not satisfactory in handling CW mode. We shall see in the following paragraphs that how this problem is solved.

Surface treatment for cathodes As we have discussed in section 2, the reverse Penning CW mode is field geometry dependent. It can be ignited even if the deflector is in perfect condition. Although we have succeeded in suppressing almost all random mode discharges, this most destructive CW mode is still at large. We then decided to eliminate all electron emissions from the cathode by coating the negative electrode with dielectric material. This method has been used for the high energy electrostatic separators at CERN.[7)]

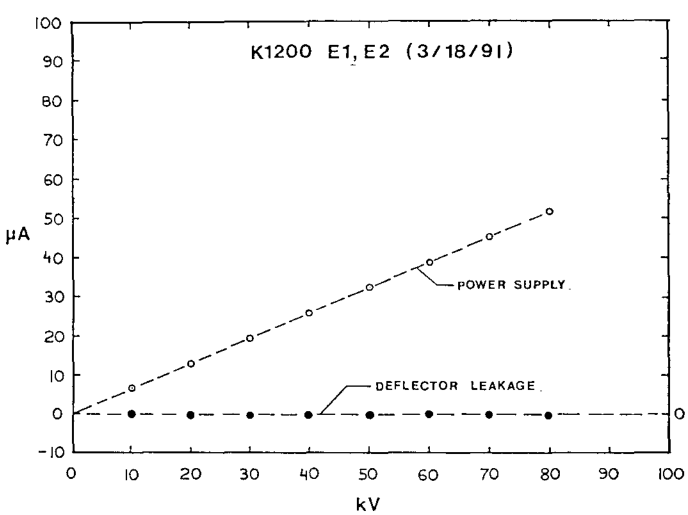

Fig. 5. Both E1 and E2 achieved 80 kV with near zero current leakage using glass coated cathode endtips.

The coating development progressed in phases and lasted about a year. At first, one endtip of a test electrode was coated with binding glass while the other end was left bare. The test electrode was put into a brute force spark test up to 110 kV. The result showed that the coated end was completely free of any discharge while the bare end went through the usual spark action as expected. In the second phase the end tips of the electrodes used for K1200 were coated. On March 18, 1992 both E1 and E2 were able to hold 80 kV at near zero leakage current in stable condition *for the first time.* The leakage current vs. applied voltage is shown in Fig. 5. Since then both E1 and E2 have been routinely operated with high reliability.

Still of concern was the fact that much of the electrode surface was uncoated. Thermal or non-thermal field emissions, emissions from attracted dirts and ExB CW mode were not yet eliminated. The third phase of this operation is to develop a technique to coat the entire length of the electrode except for a 6 mm band in the median plane. The fully coated electrode works extremely well for the single-segment E2. *All* discharge modes are suppressed. No sign of spark or CW mode damage is detected on the anode plates after 6 months of operation. The plates are found undistinguishable from a new set.

For the three-segment unit E1, the electrostatic performance is also excellent. However, the beam height in the E1 channel is taller than the uncoated bandwidth. The coating reacts to the impinging beams in some uncontrollable manner. Many micro-explosions from the surface of the glass occurred until the glass layer is eventually cleaned by the beams. The E1 finally takes beam up to half μA at stable operating condition.

The glass coating technique requires high level skill to implement, and the high quality coating is quite difficult to obtain. Industry produced anodized Aluminium surface might be a better alternative. Such electrode was prepared and put into E2 for test. The electrostatic performance is the best so far—very easy to condition to 80 kV, can be turned on full voltage like turning on

RF, etc. It is observed that the electron emission under beam bombardment seems to be much higher than the glass coated counterpart. The aluminium atoms in the oxide compound may be displaced by the impinging beams thus contribute to the higher electron emission. More operation experience will be acquired in the next few months.

4. CONCLUSION AND FUTURE PLAN

The R & D study on the K1200 deflector for the past few years provided us the basic understandings on various discharge mechanisms. The treatments to eliminate these discharges led to a 80 kV capability. The 80 kV with near zero current is chosen as an intermediate goal at this stage of development, since 60-65 kV is required for certain beam energies specified by experimenters. The future demand calls for a reliable 80-90 kV and a stable operation for extracting high external beams. Thus the goal should be a voltage holding capability of 100 kV. To achieve this goal,it is necessary to take a complete review and assessment over the quality of every subsystems. For hardware improvement, the immediate efforts will be:

1. Adding cooling capability to E1 negative electrodes
2. Special treatment for E1 on the hinge joints and beam entrance collimation
3. Acquisition of higher rating HV power supplies (120kV, 25nA)
4. Further refinement in making dielectric coating, support insulators and HV feedthrough.

In addition, the relationship of beam quality, beam tuning and extraction efficiency to the performance of deflector at high beam extraction will be studied. Further research on the HV discharge in vacuum under the influence of high magnetic field and the bombardment of high energy heavy ions will be continued.

5. ACKNOWLEDGEMENT

The authors wish to thank the NSCL operation group for their constant cooperation and assistance given to the deflector test program. Thanks also go to the design department and the machine shop who responded to our shop requests promptly. Numerous helpful discussions with Dr. Diamond of Chalk River, practical suggestions from Dr. Roger of Texas A & M are deeply appreciated. Finally we want to thank Prof. Austin and Prof. Blosser, Directors of NSCL, for their vision to set this program at 1st priority.

6. REFERENCES

1) Mesyats, G.A. and Proskurosky, D.I., **Pulsed Electrical Discharge in Vacuum** (Springer-Verlag, Berlin, 1989), ch.8.
2) Latham, R.V., "Prebreakdown Characteristics of HV Electrodes", presented at the 14th Int. Sym. on Discharges and Electrical Insulation in Vacuum, Santa Fe, New Mexico, Sept. 17-20, 1990.
3) Nolen, J.A., et.al, "Status of electrostatic deflector of the MSU K500 cyclotron," Proceedings of the 10th Int. Conf. on Cyc. E. Lansing, April 29-May 3, 1984, p.571.
4) Private communication.
5) De Martinis, C. and Ferrari, A., "High Voltage Experiments for the Electrostatic Deflector of the Milan Superconducting Cyclotron", presented at the 11th Int. Conf. on Cyclotrons and Their Applications, Tokyo, Oct. 13-17, 1986.
6) Diamond, W.J. et. al., "The Electrostatic Deflector of Chalk River Superconducting Cyclotron", presented at the 13th Int. Conf. on Cyclotrons and Their Applications", Vancouver, July 6-10, 1992.
7) Rohrbach, F., "Investigation of the Properties of Oxide-Coated Aluminium Electrodes", Proceeding of the 1st Symposium on Insulation of High Voltages in Vacuum, 1964, pp.393.