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ELECTRICAL DESIGN OF ELECTROSTATIC
DEFLECTORS FOR SECTOR-FOCUSED
CYCLOTRONS

Berkeley, California

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ABSTRACT

The new sector-focused cyclotrons have more energetic and better focused beams at the extraction radius than do ordinary cyclotrons. While the first characteristic requires a more intense electric field, the second permits this field to extend over a smaller volume. By tailoring the electrode geometry to these characteristics of the beam, the required deflector gap and electrode surface become smaller, and a higher gradient can be held without sparking. A different compromise between radioactivity, power dissipation, and resistance to spark damage must be made in selecting electrode materials. Carefully designed electrostatic deflectors perform very well in sector-focused cyclotrons of intermediate energy. Deflector efficiencies of about 50% and external-beam intensities of $20 \mu\text{A}$ have been obtained in the Lawrence Laboratory's 88-Inch Cyclotron.

ELECTRICAL DESIGN OF ELECTROSTATIC DEFLECTORS FOR SECTOR-FOCUSED CYCLOTRONS*

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INTRODUCTION

Because of the advance of the art of magnet design and improvements in the regulation of the electrical parameters of the machine, the beam of the sector-focused cyclotron is more stable and better focused than it was in the conventional cyclotrons. The higher energy of these new machines requires a higher electrical gradient than the older type, but it is not prohibitively high and simply requires the same considerations as the other parts of the machine. We have been able to extract the particles that need almost the highest gradient, 50-MeV protons, from the 88-Inch Cyclotron.

The key to deflector design is the art of tailoring the electrodes to the geometry of the beam. For the 88-Inch Cyclotron the highest gradient required is 150 kV per cm. At extraction radius the height of the beam of useful particles is about 0.25 in. The required deflector gap at the entrance is governed by the radial oscillations of the beam. Further down, the deflector gap is determined by the requirement of accommodating the different trajectories of the various beams. To provide a gradient of 150 kV per cm at the entrance, we need a gap of about 0.25 in. and a voltage of 95 kV. This condition should be provided with as much sparking margin as possible.

There is extensive literature on vacuum sparking, but so far as the mechanism of spark initiation is concerned, the researchers do not yet appear to be in agreement.¹⁻⁴ In 1952 and 1953 a sparking study was made at Lawrence Radiation Laboratory under the direction of E. Lofgren. This study revealed much information that is particularly applicable to the sparking problems associated with particle accelerators. The group directly involved with the experiments included: H. Heard, W. Kilpatrick, W. Chupp, E. Lauer, P. Byerly and a supporting staff. The sparking tests were performed using dc and rf at 14 Mc with and without a magnetic field.

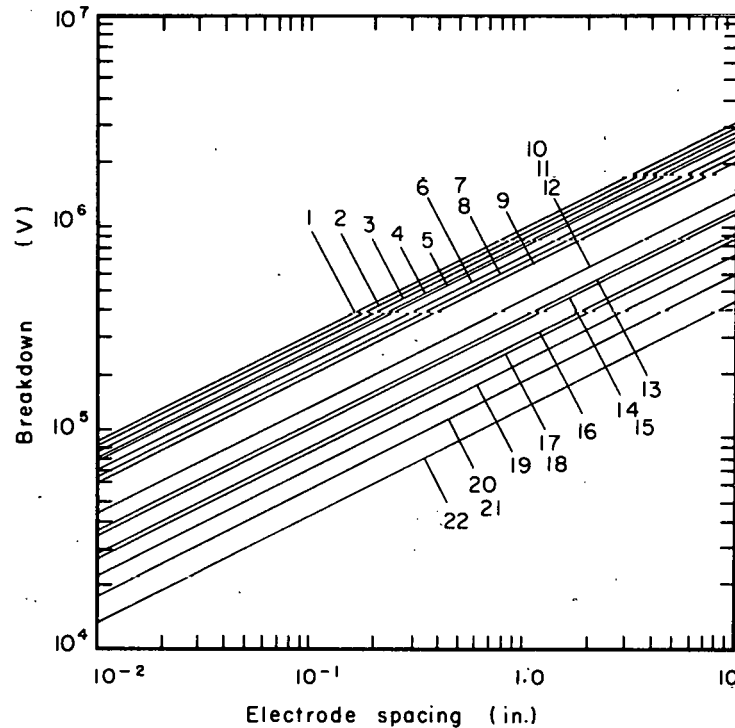
For the 14-Mc test, Heard and Chupp used a cyclotron magnet and a quarter-wave resonator and oscillator.⁵ The oscillator could deliver more than 1 MW of rf power. The gap was about 5-3/4 in. Using this equipment, Chupp and Heard found that the magnetic field increased the spark damage to the electrode surfaces very markedly. By baking in the electrodes without the magnetic field and observing the voltage at the first spark with the field, they found that the magnetic field did not reduce the voltage that the gap would hold, but after many sparks the increased gradient caused by the spark craters in the electrode surfaces reduced the voltage that the gap would hold. There seemed to be a critical magnetic field for each material beyond which the spark damage was severe and below which the spark damage was negligible. The critical fields ranged from 4 to 15 kG. This suggests that during the bake in process of a deflector there may be an advantage in reducing the magnetic field to a sufficiently low value so that the spark damage is negligible, but still with sufficient field to confine the discharge paths to the surfaces that spark under cyclotron operations.

Chupp and Heard measured the breakdown voltage and gradient for a number of gaps and confirmed the VE relationship: that for equal probability of sparking with given materials, the product of gap voltage and cathode gradient is a constant. They tested many materials for spark damage and for voltage-holding ability in the presence of the magnetic field. The voltage versus electrode-gap curves for these materials, with the VE relationship assumed to be constant, are shown in Figs. 1 and 2.

So far as spark damage is concerned,⁴ stainless steel, inconel, molybdenum, K-monel, titanium, and nickel seem to be comparable and were the best materials.⁵⁻⁷ Copper, tantalum, and aluminum were intermediate. Silver showed the most severe spark damage. Carbon appeared to resist spark damage well, but would not remain baked out. Heard and Chupp claim that after baking out carbon electrodes and turning the voltage off for even a few minutes, the whole bake-in process had to start over again. The spark dust of K-monel and nickel was found to be magnetic. That from stainless steel and the other materials tested was not.

A similar set of tests were performed without a magnetic field,⁶ using dc on the electrodes. The VE relationship was checked from 0.2 to 5.0 mm in these tests. Overall, the VE relationship has been checked experimentally and found to be valid from 0.2 mm to at least 8.5 cm.

An interesting bit of information applicable to sector-focused cyclotron deflectors is the effect of the electrical-energy storage on the voltage to which the gap will bake in.⁶ In a particular gap with a total capacitance of 24 pF, Heard found that the breakdown voltage was 10 kV after reaching equilibrium. Then, when a 0.0125- μ F capacitor was added across the gap, the electrodes baked-in to 60 kV, a six-fold increase. Adding a 0.5- μ F capacitor across the

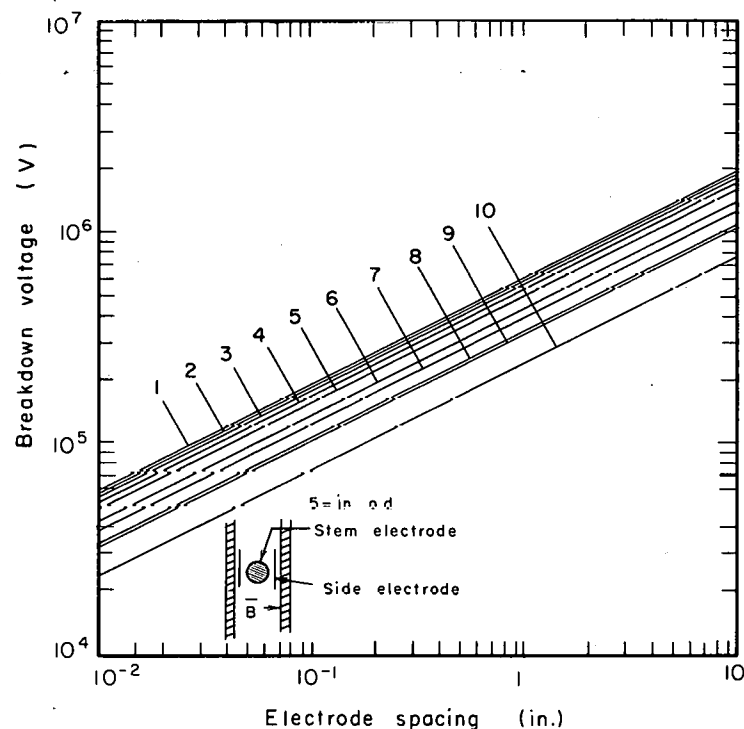


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Fig. 1. Direct-current breakdown voltage vs gap for the most important high-voltage-electrode materials, with no magnetic field, a mercury-pumped vacuum of 10^{-7} mm Hg, and a $0.0125\text{-}\mu\text{F}$ capacitor across the gap. Electrode materials tested include:

- | | |
|-------------------------------------|---------------------------|
| 1. invar | 11. unbaked 0.001-in. |
| 2. 316 stainless steel | chrome-plated copper |
| 3. manganese steel | 12. hot-rolled steel |
| 4. general plating alloy No. 720 | 13. ETP copper |
| 5. case-hardened steel | 14. Cu-P alloy |
| ($R_c = 60$ to 65) | 15. tantalum |
| 6. 0.001-in. chrome-plated | 16. 2 S aluminum |
| copper baked at 500°C | 17. lead |
| 7. inconel | 18. vacuum-fused copper |
| 8. 32% nickel steel | 19. 75 ST-6 aluminum |
| 9. Hastalloy 8 | 20. anodic carbon |
| 10. nickel | 21. spectrographic carbon |
| | 22. silver |

Data are taken from Heard,⁵ who used 2-in.-diam hemispherically capped cylinders under ideal sparking conditions.



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Fig. 2. Breakdown voltage vs gap in a strong magnetic field for the most important high-voltage electrode materials:^{5,7}

- | | |
|-------------------------------|---|
| 1. titanium | 6. duraluminum 5R-SO plus nickel |
| 2. stainless steel | 7. tantalum and DHP-copper (Rockwell 890) |
| 3. inconel | 8. silver |
| 4. OHFC-copper and molybdenum | 9. carbon |
| 5. ETP-copper and K-monel | 10. DHP-copper (Rockwell 826) |

The electrodes are the end of a $\lambda/4$ line. The energy is 10 joules at 10^6 V and a frequency of 14 Mc. The field is 15 kG for inconel, tantalum, copper, molybdenum, nickel, carbon, K-monel, and stainless 316; for other metals it is 8 kG. The oil-pumped vacuum is 10^{-6} mm Hg untrapped and 5×10^{-7} mm Hg trapped. These curves were obtained from the relationship $V = KD^{1/2}$ using the coefficients determined by Chupp and Heard.⁵ Because of the magnetic field, the conditions are more like those in a cyclotron, except that the "cleanliness" of the system was far better than one ordinarily can obtain in an operating machine.

gap reduced the breakdown voltage to 5 kV after a period of sparking. There seems to be an optimum value for the gap capacitance. Observing the spark craters Heard found that the low-capacitance gap formed small but sharply pitted craters. When the gap capacitance was increased, the size of the spark craters increased but the sharp points were melted off so that the electric field was lower. Then, with a very large amount of capacitance across the gap much more severe craters were formed. From this, one must conclude that the bake-in process is essentially a surface-heating process, and so the energy in the sparks plays an important role in the ultimate voltage a pair of electrodes will hold. Thus, in a sector-focused cyclotron the deflector power supply should permit control of the spark current.

Heard and Lauer⁸ studied the dark current that flows across the gap at voltages too low to cause a spark. The copper anode of a dc gap was bombarded in the 60-in. cyclotron to form copper-64 which was used as a radioactive tracer to find whether or not anode material was transported across the gap by the "dark current" even though no sparks occurred. The experiment was well instrumented with a photomultiplier, counting equipment, and X-ray detectors to be sure that no sparks occurred during the test. The sensitivity was sufficient to detect the presence of sparks which were not visible. They found that very large quantities of anode material are transported across the gap, even though no sparking occurs. After 1 day of operation, the increased weight of the cathode could be easily determined because of the presence of the anode material. As much as one atom of copper for every two electrons of dark current was transported across the gap. However, they were able to show that evaporation, not the electric field directly, transported most of the material.

to the cathode. No material is transported in the absence of the electric field; so, the dark current must be responsible for the anode evaporation.

The significance of this, with respect to sector-focused-cyclotron deflectors, is that where the anode surface has to be of a different material than the cathode, the anode material will appear on the cathode. Thus, if the anode material will not hold as much voltage as the cathode material, the gap may hold less voltage than would otherwise be expected.

To study this dark current further, Heard⁴ completely rebuilt the vacuum system, sandblasting all surfaces, and replacing all vacuum seals with metal gaskets, thereby eliminating all organic compounds. Mercury was used as the pumping fluid in the diffusion pumps. When he checked the dark current he found that it was more than three orders of magnitude lower than it had been in the oil-pumped vacuum system. Then, in order to pursue this result further, he froze some of the diffusion-pump oil in liquid nitrogen and put it in the mercury-pumped vacuum system. The dark current remained at the same low value as before. Then he melted the diffusion-pump oil and the dark current increased the three orders of magnitude and became the same as it was with the oil-pumped system; thus showing that the high dark current is truly a result of the diffusion-pump oil. Heard concluded that the source of the high dark current in the presence of the oil vapor is a result of carbon appearing at the electrode surfaces when the oil hydrocarbon is decomposed by the intense electric field.

It appears that the dark-current drain of the deflector in sector-focused cyclotrons could be reduced if the hydrocarbons were eliminated from the cyclotron vacuum system. In most cases this is not practical.

Next, Heard built a Müller field-emission microscope so that he could observe the nature of the electron emission.⁶ He found that it originated from

a multitude of small points, probably spicules, which increase the gradient locally.

Estimates of the gradient by T. J. Lewis indicate that the emission which occurs at macroscopic gradients of 10^3 to 10^5 V/cm is not quite field emission in the ordinary sense but, instead, is really Schotky emission.⁹ He claims that the known dimensions of surface spicules do not account for sufficient field magnification to produce the current predicted by the Nordheim-Fowler equation. Heard estimates that the current densities associated with the emission from the spicules is sufficiently high to heat the surface and provide thermionic emission at the field corresponding to spark initiation.

Using a traveling-wave oscilloscope with a sweep speed of 10 nsec/cm, Heard¹⁰ photographed the initiation and spark buildup process. These pictures are remarkable. He observed that there is a slow rise in current following the initiation which precedes the main spark current buildup. The amount of time between initiation and the large spark current buildup depends on the anode-to-cathode spacing. It seems clear that the spark is initiated by a source of electrons, but does not build up until positively charged particles from the anode reach the cathode.

Heard measured the breakdown voltage as a function of the number of sparks for a large number of materials.⁶ He found that all of them baked in in a similar fashion except 316 stainless steel, which required about ten times as many sparks to reach the ultimate breakdown voltage. It takes about 30 sparks per cm^2 to bake in high-voltage-electrode surfaces. Since it takes about a second for the vacuum to recover following a spark, the bake-in time of an electrode is about 30 sec/cm^2 .

In another series of experiments, Heard and Lauer¹¹ showed that small particles, such as dust or the granular particles produced by a spark, which fall into a high-voltage field can initiate sparking.

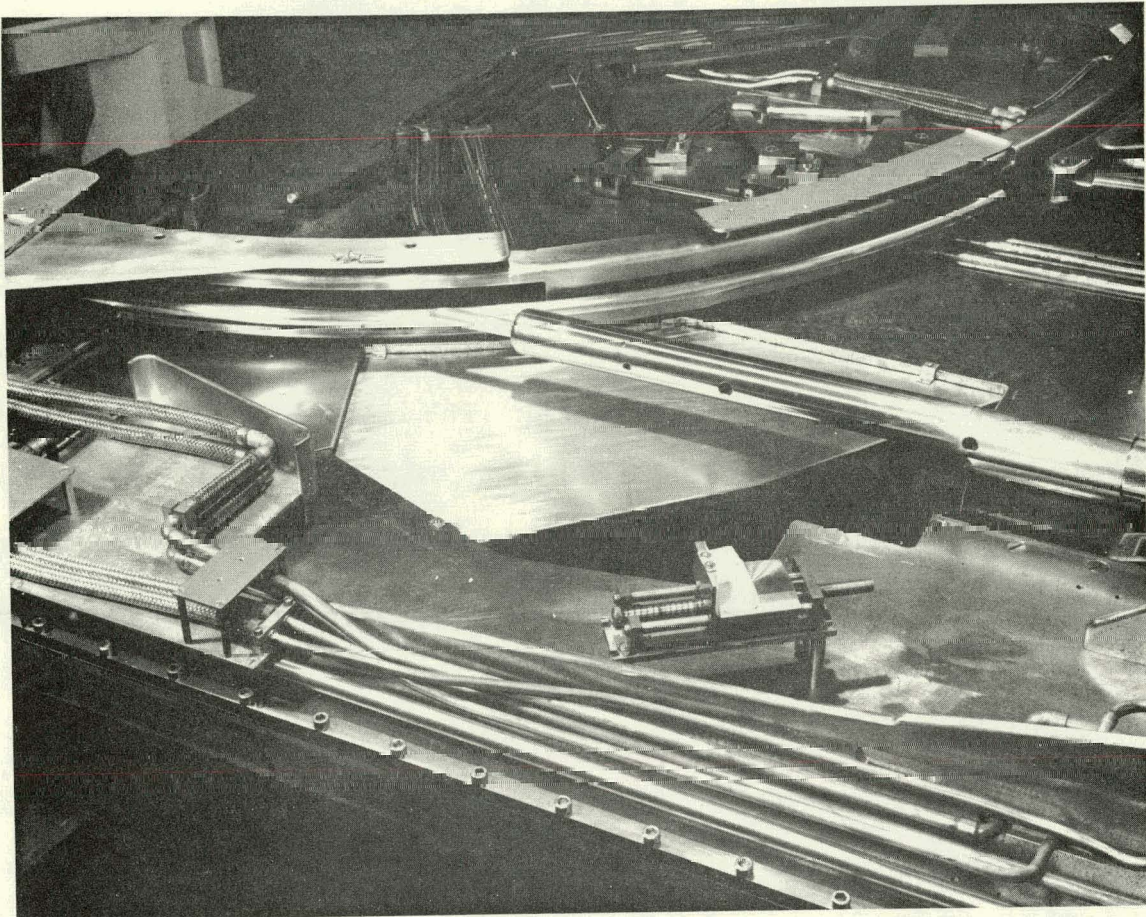
Another material for electrodes, which has been used recently by J. Murray, is glass.¹² These electrodes hold much higher voltages in practical vacuum systems than ordinary materials do because of a different mechanism for preventing spark initiation. The glass cathode has a sufficiently high specific electrical resistance so that the voltage drops through the glass in the vicinity of an emitting spicule and limits the emission current. With these electrodes, Murray has been able to produce electric fields in accelerator-type operation which are comparable to those in the sparking tests.

Glass electrodes have been used very successfully in experimental equipment for the Bevatron where the beam power is insufficient to produce serious heating. It seems improbable that glass electrodes would stand the beam power densities that we have near the input end of the deflector of a sector-focused cyclotron, but they might conceivably be applicable downstream where the beam can be stopped only at grazing incidence.

A TEST-MODEL DEFLECTOR

We decided to build a test-model deflector to obtain design data for a final deflector for the 88-Inch Cyclotron (Fig. 3). It was built inexpensively without water cooling or positioning controls.

To proceed with this experiment we needed a sparking hypothesis upon which to base the design factors to be tested. We adopted the following sparking hypothesis: The deflector high-voltage electrode contains innumerable electron-emitting spots each of which serves as the cathode for a vacuum



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Fig. 3. Test-model deflector as first installed. It was uncooled and without a positioning mechanism except for set-screw adjustments. The ground electrode was part of the original deflector and had cooling and positional adjustments so that the gap could be varied for the tests.

spark. These cathodes consist of such things as foreign contaminating material, spicules, and the gradient magnifying edges of the crystals of the electrode material. If we assume gradient magnification, the ground electrode of the deflector provides sufficient gradient at the cathode spots to produce some field emission. The dimensions of the cathode at this stage are so small that this field emission (though a very small current) involves a sufficiently high current density to heat the cathode to thermionic emission temperature. Perhaps the slow current buildup in Heard's photograph is a result of the thermionic heating of the cathode.¹⁰ Thus, the emission current increases with the electric gradient at the cathode. The electrons follow the magnetic field lines until they reach the spark anode. The power density here is thus proportional to the total voltage and the electron current density. When the power density is sufficient to vaporize the anode, a gaseous discharge occurs which we call a spark.

In the design of an electrostatic deflector for a cyclotron, we believe that the high-voltage electrode should have the minimum possible surface area. This minimizes the amount of sparking required to bake out the cathode spots and reduces the amount of electrode contamination by foreign material from dee sparks or vaporized material.

Since the beam height of the 88-Inch Cyclotron at extraction radius is no more than $1/4$ in., we decided to provide a useful electric deflecting field with a height of $1/2$ in. This allows a margin for misalignment of the deflector electrodes and possible displacement of the median plane. The required width of the electric field is determined by the necessity of accommodating incoherent radial oscillations and the change of orbit shape due to the change in flutter of the machine. The required radial extent of the electric field is not yet

known precisely, but seems to be between 0.1 and 0.4 in.

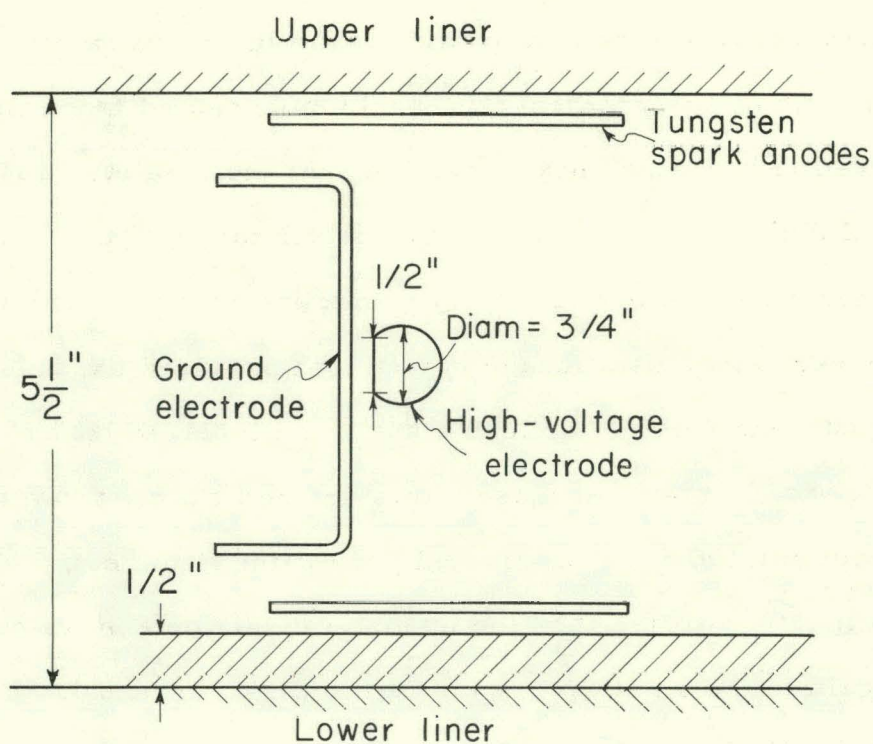
The minimum radius of curvature of the high-voltage electrode should be large enough to prevent appreciable field-gradient magnification. In practice, the minimum radius should be no less than about half a gap.

The cross-sectional dimensions of the high-voltage electrode determined from these considerations are shown in Fig. 4. The high-voltage electrode was fabricated and cantilevered from the high-voltage bushing.

The first tests of this configuration showed that at smaller gaps the electrode did not hold the gradient that would be expected from the VE relationship. Observation revealed the explanation. At the smaller gaps the electrode vibrated like a tuning fork in a tuning-fork oscillator.

The mechanism of oscillation is rather interesting. The forces driving the electrode were electrostatic; the device that provided the pulsating force was the dark current. As the deflector bar was displaced toward the ground electrode, the dark current increased; this drained charge from the electrode, reducing the potential and the force, and permitting it to return to its neutral position. Its inertia carried it in the opposite direction and its compliance returned it again to the smaller gap where the dark current drained off further charge. The oscillation built up; the energy coming from the electric field, until the gap was so small that it sparked.

To pursue this from another point of view, one can think of the emission of dark current as being analogous to the emission current in a vacuum tube. The change in this current by the electrode displacement is analogous to the change of the space current in a vacuum tube by the potential of the grid. Thus, a slight change in position of the electrode makes an enormous change in dark current, just as a slight change in potential on the grid of a vacuum tube



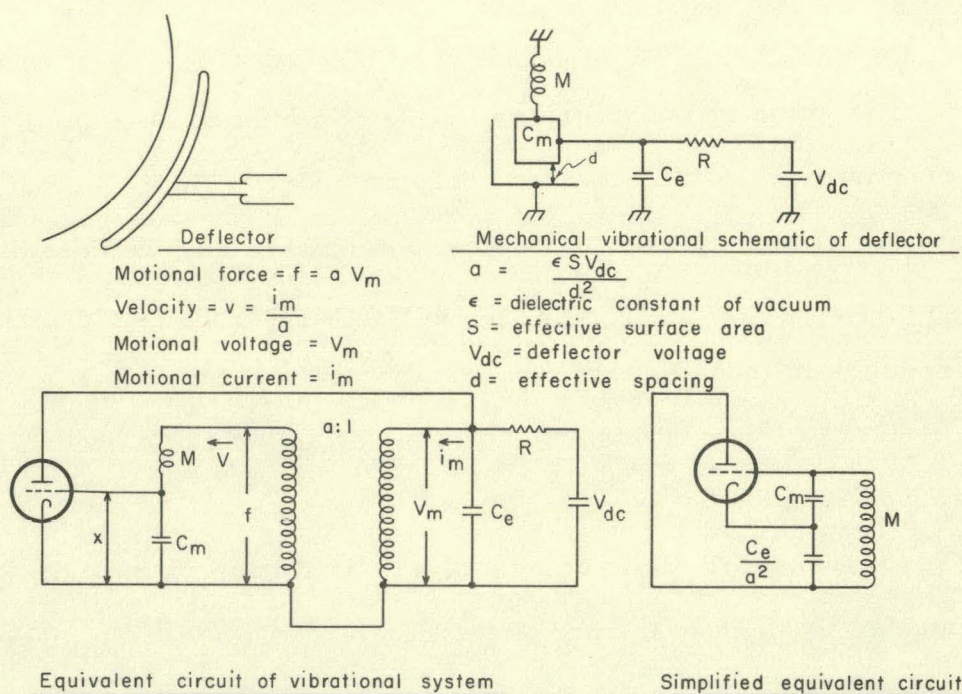
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Fig. 4. Critical dimensions of the test-model deflector. The tungsten spark anodes were installed during the latter part of the tests.

provides a large change in space current within the vacuum tube. Next, one can draw the electromechanical equivalent circuit of the system, using a transformer for the conversion from mechanical to electrical units as shown in Fig. 5. Through the force-voltage analogy, velocity becomes analogous to current. The velocity is integrated by the compliance, producing a voltage that is proportional to the electrode displacement. Thus, the potential across the compliance corresponds to the grid potential of our vacuum tube. Using this technique, one can draw an electromechanical equivalent circuit.¹³ The circuit reduces to that of a Colpitts oscillator, as shown in Fig. 5. The buildup of oscillation was observed on the voltage of the deflector with an oscilloscope (Fig. 6).

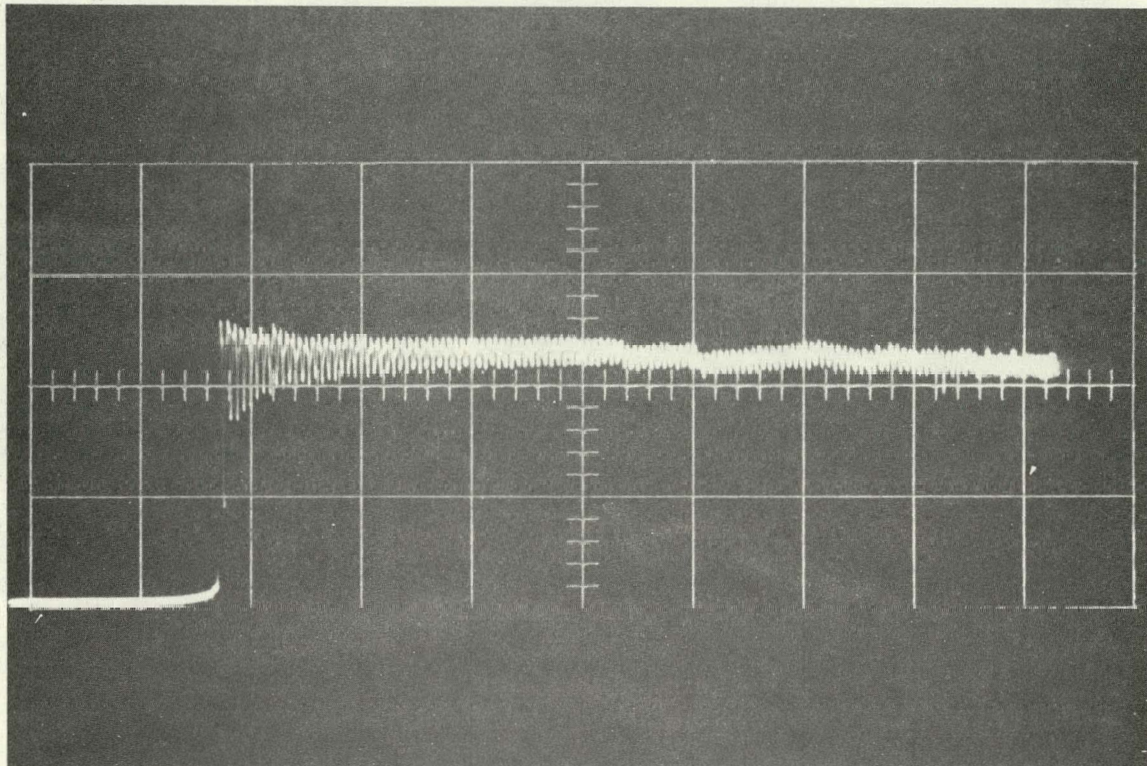
To prevent this electromechanical oscillation, a pair of insulators were installed to support the high-voltage electrode (Fig. 7). The deflector was now baked in for deflector spacings of 0.2, 0.3, and 0.4 in. The breakdown voltage followed the VE curve, as shown in Fig. 8.

For this test we built a deflector power supply designed specifically to give us control of the bake-in process in the hopes of improving the deflector voltage. The power supply, described in reference 14, consists basically of a six-stage Cockcroft-Walton rectifier built from silicon diodes and operating at 110 kc. It stores very little energy--only 2.5 joules at 120 kV. It is driven by a vacuum-tube oscillator which has a "crowbar" on the screen grid so that the flow of power to the deflector can be cut off within a few microseconds following a spark. We found that, by making the crowbar current control available to the operator, the amount of energy in each spark can be optimized and a higher VE number can be obtained. With this control, the intensity of the sparks can be varied through a wide range--from invisibility to heavy arcs.



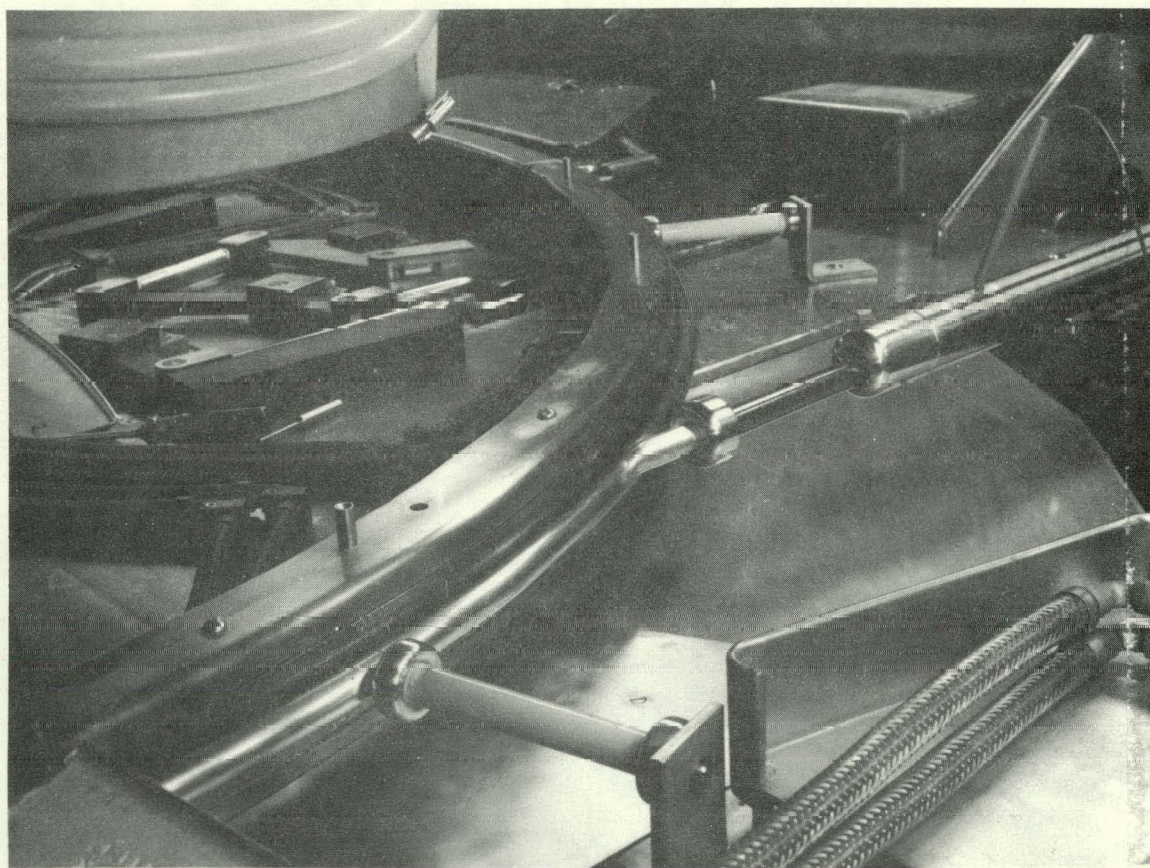
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Fig. 5. Mechanical-vibrational schematic of the deflector, and equivalent circuits for the system. (a) Test-model deflector having vibrational nodes similar to a tuning fork. The vibrational system can be simplified to an equivalent mass and compliance, and a mechanical schematic (b) can be drawn. By means of the force-voltage electromechanical analogy, an equivalent electrical circuit (c) can be drawn. The deflector dark current can be simulated by the anode current in a vacuum tube. The change in dark current with electrode displacement is analogous to the change in anode current with grid potential of a vacuum tube. The grid potential is proportional to the displacement of the electrode, which is proportional to the integral of the velocity of the compliance. Simplifying this circuit by the techniques of network analysis the system reduces to that of a Colpitts oscillator.



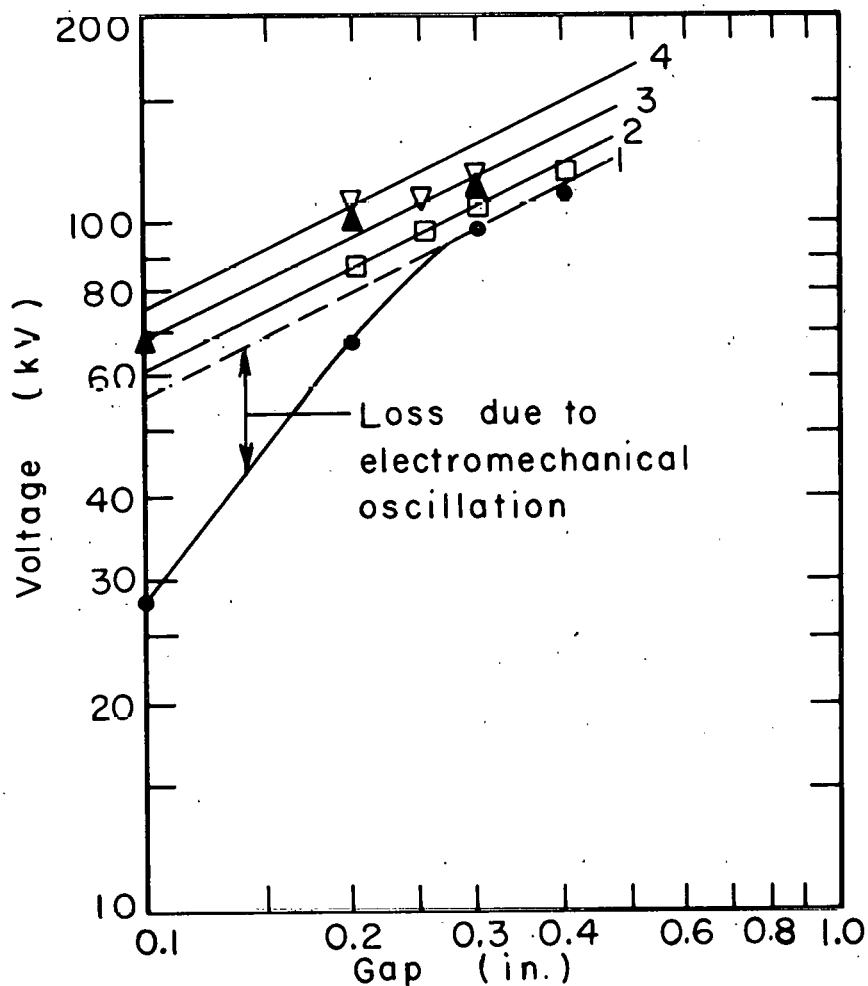
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Fig. 6. Buildup of electromechanical oscillation observed on the deflector voltage input of the deflector regulator. The sweep speed is 100 msec/cm. The period is 50 msec corresponding to a vibrational frequency of 20 cps.



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Fig. 7. Support insulator which prevented electromechanical vibration.



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Fig. 8. Voltage-vs-gap curves for the different tests of the test-model deflector. Curve 1 was taken before insulators were installed and electromechanical oscillation occurred, resulting in $VE = 1.23 \times 10^4 (\text{kV})^2/\text{cm}$; curve 2 was obtained with insulator supports which prevented electromechanical oscillation, crowbar was set at 0.4 A, resulting in $VE = 1.47 \times 10^4 (\text{kV})^2/\text{cm}$; in curve 3, the crowbar was adjusted to optimize voltage, resulting in $VE = 1.88 \times 10^4 (\text{kV})^2/\text{cm}$; curve-4 conditions are the same as for curve 3 except tungsten anodes were used, resulting in $VE = 2.27 \times 10^4 (\text{kV})^2/\text{cm}$. Points greater than 110 kV may have been limited by parasitic oscillation in the power supply.

Another technique which proved helpful is the use of spark anodes. According to our sparking hypothesis, a spark occurs when the power density at the anode in the initiating electrons is sufficient to vaporize the anode material. If one uses an anode material that vaporizes at a higher power density, it should be possible to hold a higher voltage. We decided to try tungsten for this purpose to see if any improvement could be achieved. In the previous tests the anode for the sparks was either the K-monel base plate or the inconel canopies, or, over part of the deflector, the copper liner of the vacuum tank. None of these, of course, are high-temperature materials. All that we had available for this experiment was some 2- by 8-in. sheets of 15-mil tungsten. They were installed with the edges overlapped so that only the tungsten would be exposed to the sparks. Before this test the best VE number that the deflector had held was $1.93 \times 10^4 \text{ (kV)}^2/\text{cm}$. With the tungsten anodes, the VE number increased to $2.25 \times 10^4 \text{ (kV)}^2/\text{cm}$: an increase of 17% in VE number. In addition, we found that the tungsten anodes resisted spark damage better than other materials.

Another series of tests was designed to see the effect of deflector capacitance on VE number. Heard's sparking test had shown that there was an optimum capacitance for a spark gap. Also, he had found that, for a given amount of electrical energy, the spark damage was very much increased if there was a magnetic field present. However, his tests of breakdown voltage versus gap capacitance were conducted without a magnetic field. Therefore it seemed likely that the optimum deflector capacitance would be less than he found in his tests. Our first test was made before we had the crowbar control available to the operator and before we had tungsten anodes. To find out if a lower capacitance would improve the VE number, we installed a resistor in

the vacuum system near the high-voltage electrode, so that we could isolate the capacitance of the system from the deflector electrode. (It can be shown that the energy in the capacitance on the power supply side of the resistor does not flow into the spark, but is dissipated in the resistor.) We found no appreciable difference.

Up to now, the crowbar control was set at 0.4 A (its range is 0.1 to 1.0 A) and was remotely located. Next, it was made available to the operator; we repeated the measurements, optimizing the crowbar current for each case. We found that we could compensate for deflector capacitance; at lower capacitance we could crowbar at higher spark currents, and vice versa. Then, the VE number showed no significant dependence upon capacitance from 67 to 580 pF, which was the maximum available range (see Table I.).

We checked the VE number for dependence upon the magnetic field for the entire range of magnet currents of the 88-Inch-Cyclotron--167 to 2500 A. There was no significant change in VE number. We optimized the crowbar current setting for each point.

From these tests we can conclude the following in regard to deflector design: (a) The electric field should be matched to the cross-sectional dimensions of the beam so that the amount of high-voltage surface can be kept to a minimum. (b) The deflector power supply should be designed to provide control of the amount of heat in the sparks. (c) The high-voltage electrode must be rigidly mounted to prevent the formation of electromechanical oscillation. (d) Tungsten spark anodes should be employed. (e) Deflector capacitance should be kept reasonably low, but with tungsten spark anodes and spark current control from the power supply, at least 600 pF of deflector capacitance can be tolerated without loss of VE number. (f) A VE number of at least

Table I. Deflector voltage for various settings of crowbar current deflector gap, and deflector capacitance.

Deflector capacitance (pF)	Deflector voltage (kV)	Deflector gap (in.)	Crowbar current (A)	VE number $[10^4(\text{kV})^2/\text{cm}]$
A. <u>Spark anodes: a combination of inconel, stainless steel, K-monel, and copper.</u>				
67	111.5	0.3	0.400	1.63
82	99	0.2	0.425	1.53
112	67	0.1	0.425	1.7
134	113	0.35	0.280	1.43
138	108	0.3	0.400	1.53
143	90	0.25	0.250	1.28
288	108	0.3	0.300	1.53
293	103	0.25	0.300	1.67
300	99	0.2	0.300	1.93
568	100	0.3	0.250	1.31
573	98	0.25	0.200	1.51
580	93	0.2	0.200	1.71
				Rms VE = 1.57
B. <u>Tungsten spark anodes.</u>				
138	117	0.3	0.475	1.80
143	110	0.25	0.400	1.91
150	107	0.2	0.300	2.25
568	110	0.3	0.400	1.59
573	109	0.25	0.400	1.87
580	99	0.2	0.350	1.93
				Rms VE = 1.9

$2.25 \times 10^4 \text{ (kV)}^2/\text{cm}$ can be held; a reasonable design value would be about $1.5 \times 10^4 \text{ (kV)}^2/\text{cm}$. (g) That a deflector is limited by sparking phenomena and not from an extraneous cause can be tested simply by a log-log plot of the voltage versus gap to see that it follows a VE line.

To be sure that nothing was overlooked, we decided to put a small amount of beam through the test-model deflector. The amount had to be small because of the absence of water cooling and a positioning mechanism for alignment with the beam.

First, we put a 65-MeV alpha beam through it. This is the beam for which we best know the characteristics. It required a higher than normal gradient, indicating that the deflector was aligned at too steep an angle with respect to the internal orbits. Scaling the gradient required for the alpha beam to 50-MeV protons indicated that about 200 kV/cm would be required at the deflector entrance. Then we retuned the machine for 50-MeV protons--the beam which in this cyclotron requires almost the highest gradient for extraction. We moved the ground-electrode structure, which is part of the original deflector and is equipped with a positioning mechanism, until the deflector gap at the entrance was 0.15 in. and at the exit was 0.25 in. With these gaps, the deflector held in excess of 80 kV, which was sufficient to provide the required gradients. The extracted beam maximized at a deflector voltage of 76 kV. This was only a small beam--0.25 μA --but it was sufficient to confirm that the gradients in the deflector were proper for its extraction.

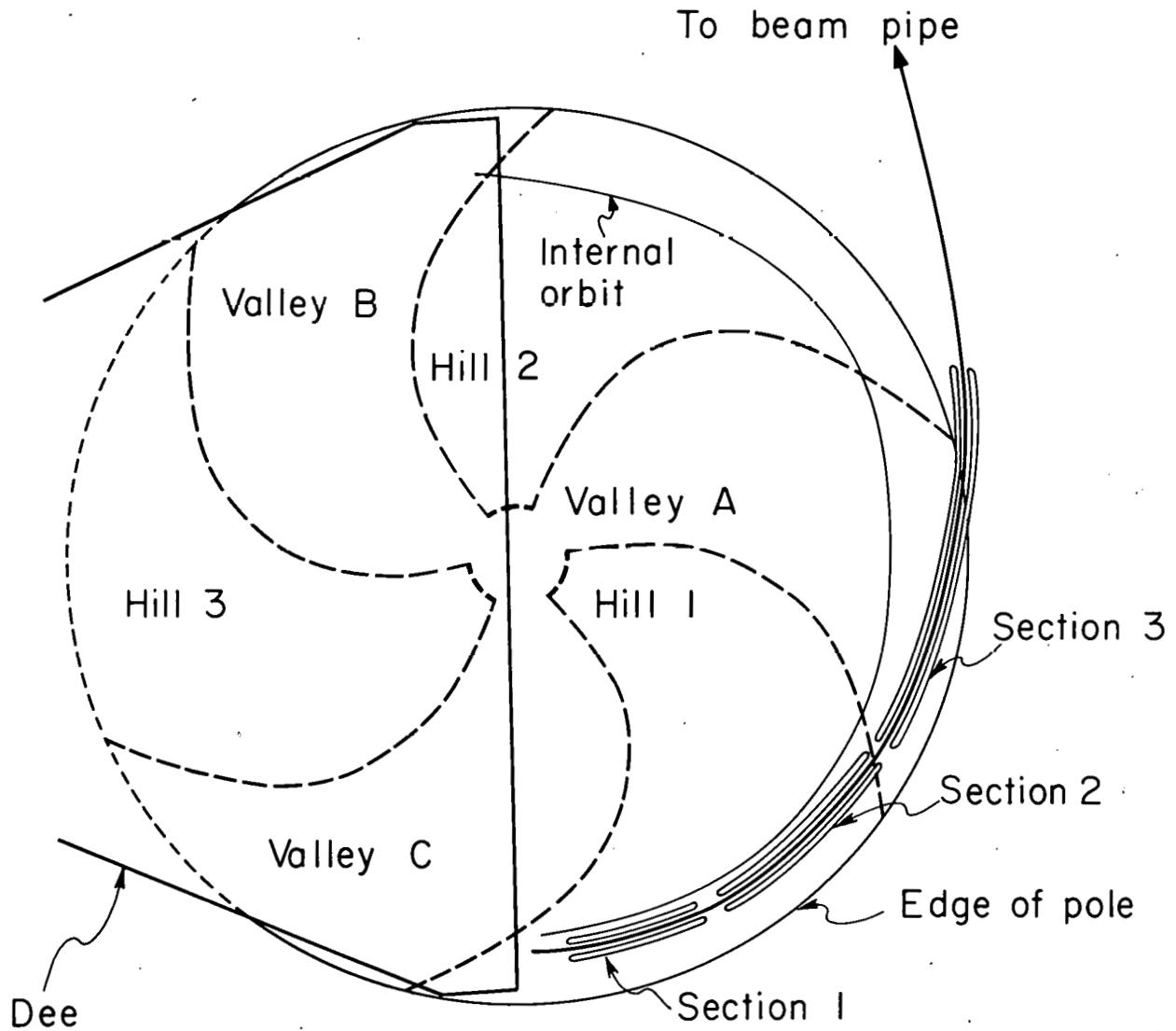
Next, we decided to see whether carbon septums could be used for the cyclotron. We were particularly interested in carbon because of its short half-lives and low activity. First, we performed sparking tests without a beam and found that where no sparking occurred to the carbon, we could obtain a VE

number of 1.7×10^4 . This is about 75% of what we had with metal septums. This number is really rather meaningless; it simply implies that the stray carbon dust was sufficiently small to contaminate the high-voltage electrode by this amount. Next, we accelerated a 32-MeV deuteron beam and extracted a few microamperes. When we increased the beam current, the carbon, evaporated from the septum, contaminated the high-voltage electrode, and very little voltage could be held. By sparking the electrode, it appeared possible to clean up the contamination, but it was an impracticably slow process. Next, we decided to find out how much beam power a carbon septum would stand. We moved the septum in several inches so that the radiated heat would not damage the deflector. A 500- μ A beam of 32-MeV deuterons did not destroy the carbon septum. It did thoroughly contaminate the high-voltage electrode and insulators though.

From these tests we conclude that, unless a solution appears to the carbon contamination problem, metal septums will be required for the high-energy beams. When one considers that sector-focused cyclotrons are capable of producing internal beams in excess of 50 kW, it is apparent that the septum is apt to be the limitation for some time. Further study of the septum problem is being planned in Berkeley.

A PROPOSED DEFLECTOR DESIGN

The next problem to consider in the design of an electrostatic deflector is contouring the electrodes to the trajectory of the beam (see Fig. 9). First, there is the problem of the beam entry into the deflector. This can be divided into two parts: the turn separation and the incoherent beam oscillations. The turn separation is important because it determines the thickness and, hence,



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Fig. 9. Possible three-element deflector. The first element would have adjustments for position and gap. The second element would have positional adjustments only. The third element probably could be fixed in position.

the thermal conductivity of the septum. The incoherent beam oscillations determine the size of the entrance gap required, hence, the maximum gradient that may be held without sparking.

The separation between turns is determined by the voltage gain per turn and the coherent radial betatron oscillation of the beam. Upon entering the deflector, the beam should be moved radially in a relatively short azimuth in order to provide clearance between the internal orbits and the downstream sections of the deflector. Every effort should be made to tailor this first section tightly to the beam so that the gap will be as small as possible and the gradient as high as possible. This section should probably be restricted to about 30 azimuthal degrees. A. Garren has computed trajectories through the deflector and found that the beam dispersion in this first section is small.¹⁵ If it contains positional adjustments and gap adjustments, the electrodes can be aligned quite closely with the beam, and the deflector gap can be made quite small.

If the second set of electrodes starts at the center of a hill of the magnet pole and has an independent set of positional adjustments, the change in radius of curvature of the trajectory with change in magnetic field can best be accommodated. The electrical-gradient requirements are not as stringent in this section of the deflector, and different beams may be accommodated without gap adjustment. The second section accepts the beam which has been separated from the orbits by the first section and aims it into the third section of the deflector. This section may not require either gap or positional adjustment if the flexibility of the second section is sufficient.

Garren's trajectory calculations show that practically all beam dispersion occurs in the third section of the deflector; it should be contoured appropriately. Upon leaving the third section of the deflector, all beam trajectories have the

same target--the center of the exit beam pipe of the cyclotron.

Each of the three ground electrodes should be insulated, so that any intercepted beam current can be monitored by the operator as an aid in aligning the deflector electrodes to the beam trajectory. Of course, this three-sector deflector is only one of several possibilities. It may provide more flexibility than is needed to accommodate all of the possible beams of the 88-Inch Cyclotron. At least it is a convenient way of illustrating the design considerations of the different parts of the deflector.

It is not clear to us why, in practical accelerators, we cannot hold VE numbers as high as is routinely done by those doing research on sparking. It seems probable that the difference has to do with the difference in experimental technique. Heard describes his efforts at electrode cleanliness in each of his papers. In reference 5, for example, he states "Previous to this run, the entire vacuum casing and traps were sandblasted, inside and outside, and washed in flowing cp acetone and cp ethyl alcohol (95%); all gaskets in the vacuum system section of this unit were made of commercial 40-60 solder the ends of which had been fused together. Insulators were coupled to the system with lead-encased gum rubber gaskets. Electrodes and holders were carefully washed with "Dreft" (a household soap) and water, distilled water, chromic acid made from 37 Ncp sulphuric acid, and finally rinsed in distilled water, cp acetone, and cp ethyl alcohol. Parts were assembled immediately with grease-free tools and paper towels; none of the parts were touched with bare hands during assembly. A typical base pressure for the system was of the order of 1 to 3×10^{-7} mm Hg on an untrapped Westinghouse 5966 ionization gauge. The lowest pressure recorded on the trapped gauge was 8×10^{-8} mm Hg.

This clearly represents a much higher degree of cleanliness than was

practical in the 88-Inch Cyclotron. So far as our vacuum system is concerned, the cleanliness represents the state of equilibrium of a cyclotron which has been in operation for little more than a year. Accessible surfaces were cleaned with a vacuum cleaner and solvent-impregnated rags. The deflector-electrode configuration was sufficiently complicated so that it could not be installed and aligned to the accuracy necessary if handling were restricted by the use of paper towels. Also, the radiation level of the ground electrode was sufficiently high that personnel exposure had to be kept to a minimum. During the sparking test, the trapped vacuum gauges indicated a pressure of about 5×10^{-6} mmHg.

Another factor which affected our experimental technique was the fact that the deflector power supply was of a new type and was being debugged concurrently with the deflector tests. The power supply's modulator would frequently break into a parasitic oscillation at deflector voltages between 110 and 120 kV. Often, when the sparking was within this range, we could not determine whether the sparks were caused by deflector-gap breakdown or by a sudden parasitic-induced change in deflector voltage. Below 110 kV, the points were unquestionably valid. Also, the power supply had an upper limit of 120 kV, so that some of the gaps were limited by the power supply rather than by sparking voltage at this point.

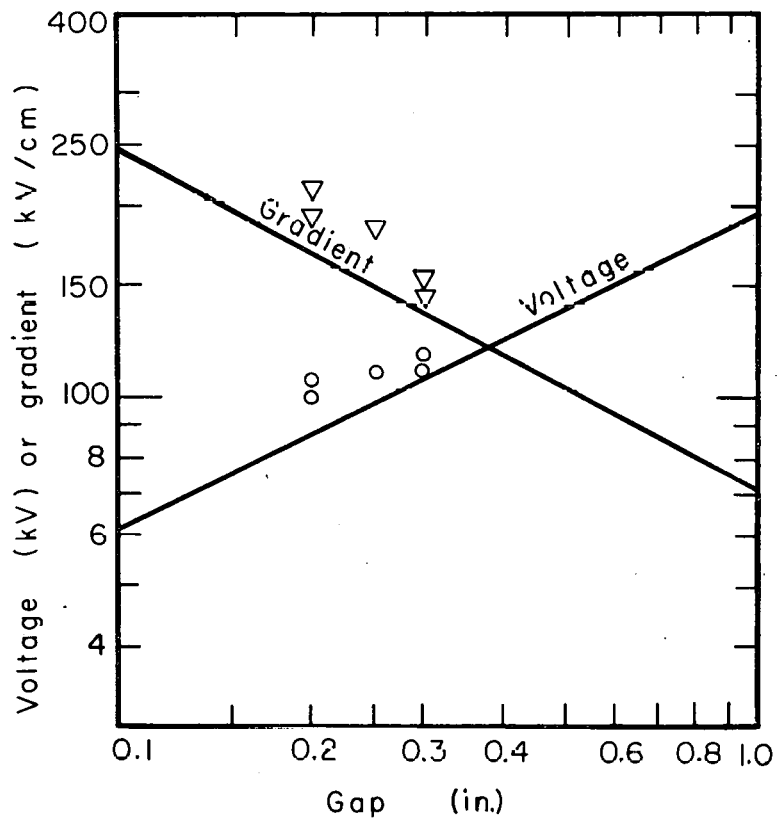
A technique used routinely at the 88-Inch Cyclotron, which works very well for cleaning the high-voltage surfaces, is called "ion scrubbing." Hydrogen is let into the vacuum tank until the pressure becomes 200 to 300 μ . Sixty-cycle power is applied directly to the deflector electrode through a 480-V transformer and a current-limiting resistor. This forms a glow discharge which surrounds the deflector. A discharge current of about 100 mA is maintained for about an hour. The theory is that the hydrogen reduces the

oxides on the electrode surface. "Ion scrubbing," typically, reduces the deflector dark current by a factor of five or so.

CONCLUSION

The techniques employed in the test-model deflector were sufficient to produce a VE number of $2.25 \times 10^4 \text{ (kV)}^2/\text{cm}$. In order to provide an adequate margin for day-to-day operation, a design value of 1.5×10^4 should be used (Fig. 10). The presence of the beam did not reduce the VE number of the deflector when a tungsten septum was used; with a carbon septum we managed to hold a VE number about three-quarters as high as with a metal septum, provided no beam was present. With a beam, carbon is evaporated and contaminates the high-voltage electrode. With an intense beam, one can easily evaporate enough carbon from the septum, to reduce the deflector's VE number to 25% of its normal value. This requires letting the machine's vacuum down to air and cleaning the deflector and insulators with solvents. In spite of carbon's terrible contamination hazard, its virtues--short half-lives, low activity, and ability to withstand very considerable amounts of power--are sufficient to keep alive our hope that some day we may find a way to use it successfully.

The septum appears to be the component of the sector-focused cyclotron most in need of research and development. At present, it limits our output beam power to only a few kilowatts. On the other hand, when we compare our external beams with those of conventional cyclotrons of the past, the progress is impressive. Our experimenters report an order of magnitude more analyzed beam current and an order of magnitude better energy resolution in their scattering chambers than they had with the older cyclotrons.



MU-30068

Fig. 10. Recommended design voltage and gradient vs gap for sector-focused cyclotron deflectors based upon $VE = 1.5 \times 10^4 (\text{kV})^2/\text{cm}$. Circles represent voltages and triangles represent gradients obtained experimentally.

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