ELECTRICAL DESIGN OF ELECTROSTATIC DEFLECTORS FOR SECTOR-FOCUSED CYCLOTRONS(*)

B.H. Smith and H.A. Grunder
Lawrence Radiation Laboratory, Berkeley
(Presented by B.H. Smith)

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 beam1). For the 88 Inch Cyclotron the highest gradient required is 150 kV/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/cm at the entrance, we need a gap of about 0.25 in. and a voltage of 95 kV. Because of sparking, this condition should be provided with as much margin as possible.

We decided to build a test-model deflector to obtain design data for a final deflector for the 88 Inch Cyclotron (Fig. 1). To proceed with this experiment we adopted the following hypothesis. The deflector high-voltage electrode contains innumerable electron-emitting spots each of which serves as the cathode for a vacuum 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 are so small that this field emission involves a sufficiently high current density to heat the cathode to thermionic emission temperature. 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

---

(*) Work done under auspices of the U.S. Atomic Energy Commision.

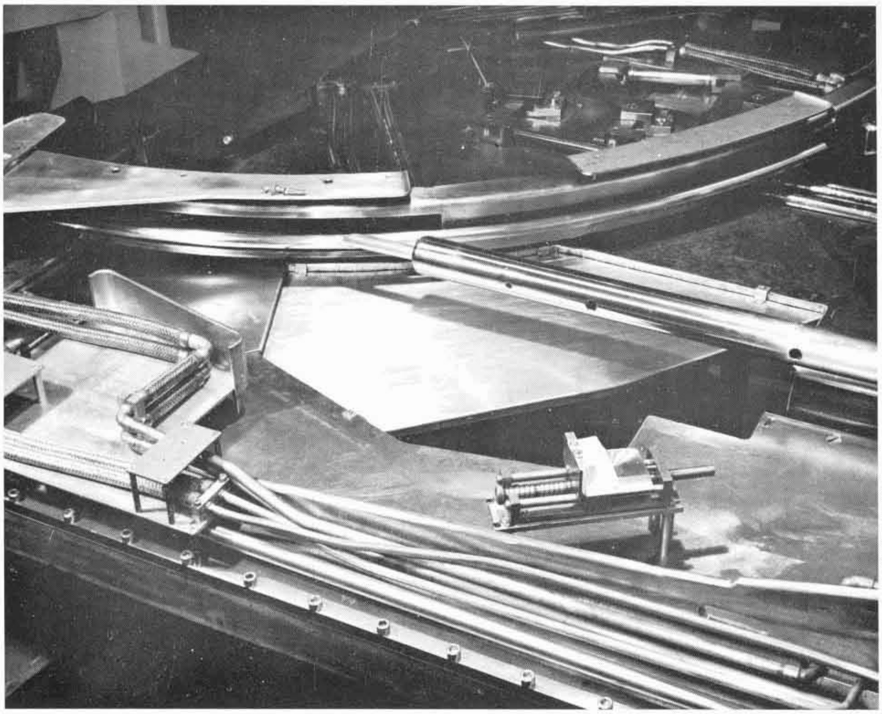

Fig. 1 Test-model deflector as first installed. It was uncooled and without a positioning mechanism except for set-screw adjustments. The ground electrode was part of the original deflector and had cooling and position adjustments so that the gap could be varied for the tests.

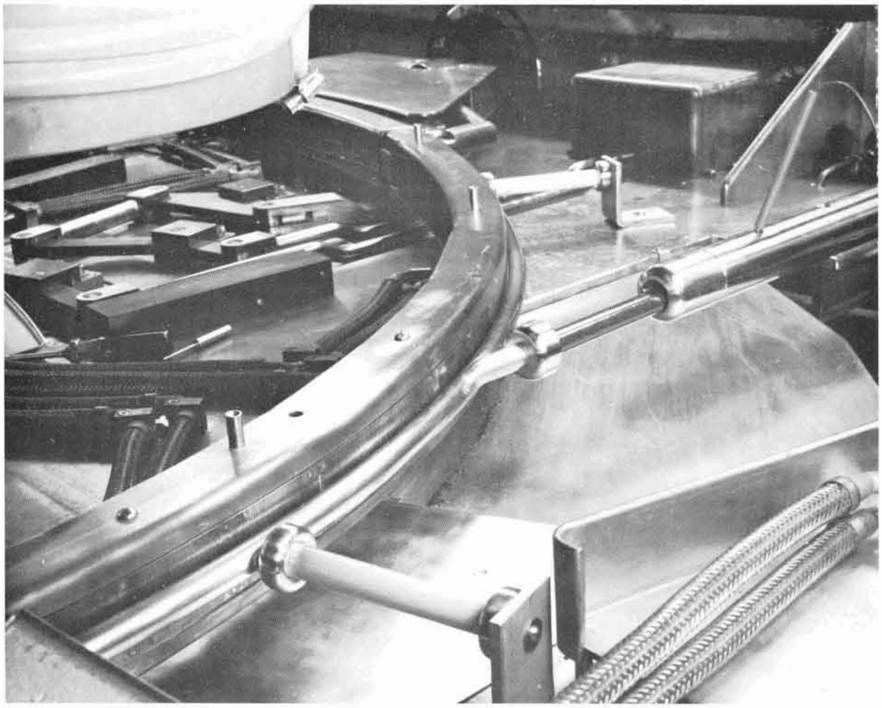

Fig. 3 Support insulator which prevented electromechanical vibration.

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 mateiral.

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-section dimensions of the high-voltage electrode determined from these considerations are shown in Fig. 2.

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 the 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 prevent this electromechanical oscillation, a pair of insulators were installed to support the high-voltage electrode (Fig. 3). The deflector was now baked in and tested for deflector spacings of 0.2, 0.3, and 0.4 in. The breakdown voltage followed the VE curve, as shown in Fig. 4.

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

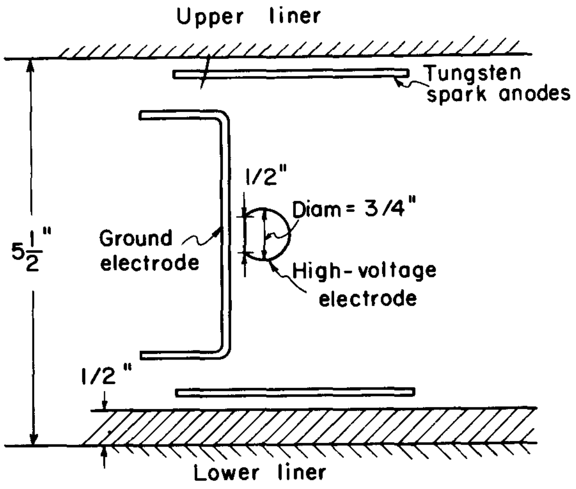

Fig. 2 Critical dimensions of the test-model deflector. The tungsten spark anodes were installed during the latter part of the tests.

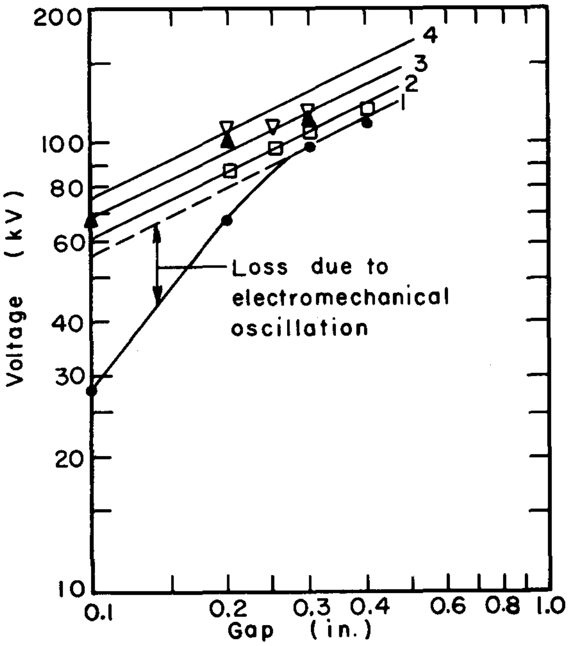

Fig. 4 Voltage-versus-gap curves for the different tests of the test-model deflector. Curve 1 was taken before insulators were installed to suppress electromechanical oscillation. Curve 2 was obtained afterward, the crowbar was set at 0.4 A, resulting in VE = 1.47 x $10^4(kV)^2$/cm. In curve 3, the crowbar was adjusted to optimize voltage, resulting in VE = 1.88 x $10^4(kV)^2$/cm. For curve 4 the conditions are the same as for curve 3 except tungsten anodes were added, resulting in VE = 2.27 x $10^4(kV)^2$/cm. Points greater than 110 kV may have been limited by parasitic oscillation in the power supply.

voltage. The power supply, consists basically of a six-stage Cockcroft-Walton rectifier built from silicon diodes and operating at 110 kc/s. 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.

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. Before this test the best VE number that the deflector had held was 1.93 x $10^4(kV)^2$/cm. With the tungsten anodes, the VE number increased 17%, to 2.25 x $10^4(kV)^2$/cm. 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$^{2)}$ 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. 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).

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 $[10^4 (kV)^2/cm]$
		A. Spark anodes : a combination of inconel, stainless steel, K-monel, and copper.		
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. Tungsten spark anodes.		
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

We checked the VE number for dependence on 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-section 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 $2.25 \times 10^4 (\mathrm{kV})^2/\mathrm{cm}$ can be held; a reasonable design value would be about $1.5 \times 10^4 (\mathrm{kV})^2/\mathrm{cm}$. 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 put a small amount of 50 MeV proton beam through the test-model deflector.

The next problem to consider in the design of an electrostatic deflector is contouring the electrodes to the trajectory of the beam (see Fig. 5). 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, 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 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. A. Garren has computed trajectories through the deflector and found that the beam dispersion in this first section is small. If it contains position 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 position 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 position adjustment.

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

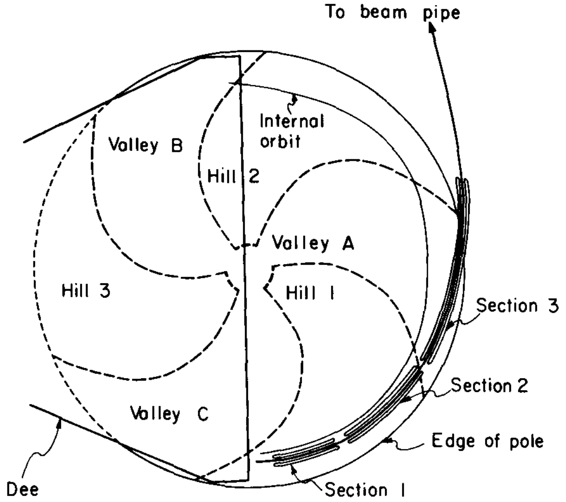

Fig. 5 Possible three-element deflector. The first element would have adjustments for position and gap. The second element would have position adjustments only. The third element probably could be fixed in position.

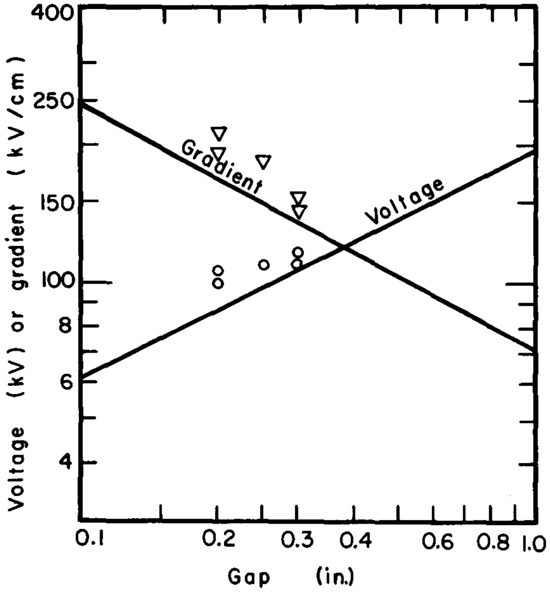

Fig. 6 Recommended design voltage and gradient versus gap for sector-focused cyclotron deflectors, based on VE = $1.5 \times 10^4 (kV)^2/cm$. Circles represent voltages and triangles represent gradients obtained experimentally.

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.

The techniques employed in the test-model deflector were sufficient to produce a VE number of $2.25 \times 10^4 (kV)^2/cm$. To provide an adequate margin for day-to-day operation, a design value of 1.5×10^4 should be used (Fig. 6). 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 VE number to 25% of its normal value. Then one must open the vacuum chamber and clean 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 kilowatt. 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.

References

1) For a more complete treatment of this work see Lawrence Radiation Laboratory Report UCRL-10654, March 25, 1963.
2) Harry G. Heard, Lawrence Radiation Laboratory Report UCRL-1697, March 1952.

DISCUSSION

LEBOUTET : Can you compare, from your experience, the voltage gradient that can be held along, and across the magnetic field?

SMITH : According to my experience, and to a great deal of sparking research done in Berkeley, there is no difference. The magnetic field seems to be of secondary importance; the emission from the spot on the cathode is just a question of gradient at that point.

ALLEN : We never observe sparks perpendicular to the magnetic field. The sparking is always along the field lines. Do you see a contradiction?

SMITH : No. A spark will initiate where the electrical gradient is sufficiently high, and will then follow magnetic field lines. I only propose this as an hypothesis in the absence of any other reasonable explanation.

SCHMIDT : Kelly reported earlier that you had difficulties with sparking in the Berkeley cyclotron, and yet this deflector seems to hold enormous voltages.

SMITH : The voltages reported here were obtained in our test model with a small inconel deflector bar. Kelly was referring to the original deflector in the machine which has much more surface and it is difficult to bake out.

LIVINGSTON : What are your recommendations on best materials to use?

SMITH : Of the many materials tested, inconel is one of the best. The material which actually held the most voltage in these tests was 3/16 stainless steel but it took many sparks to bake in, in fact about 10 times as many as for an inconel electrode.