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Experience with Back-Biased Accelerating Tubes*

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MASTER

Introduction

In this paper I shall try to convey to you some of our experiences with different ion-acceleration tubes in the large Los Alamos electrostatic machine. This machine has features that 14 years after its initial completion have not been copied. We still are improving it. Now the rage these days in high gradient tubes seems to be inclined field tubes, but I believe you will find our experiences with back-biasing interesting. As a matter of fact, they may shed more light on the insulator problem than upon back-biasing. Now I believe that the back-biased tube has more promise than the inclined field tube. I must admit that the data I will cite will not exactly prove my point. However, in my opinion, so far correct use of the back-bias principle has not been made in an acceleration tube. At any rate I want to stir up this argument.

Now it just happens, I made use of the "inclined field principle" in a spun steel electrode tube built in 1939-40 at the University of Wisconsin with R. L. Burling under the guidance of Professor R. G. Herb. See Fig. 1. This incidentally was the first spun electrode tube so far as I know. Considerable loading was present in this tube as first constructed without any inserts of course. I first thought this might be due to electron multiplication so the steel inserts were put in with no appreciable effect. Because of the reversed field on the inserts where the electrons would strike, the inserts should have been effective if electron multiplication was the problem. Then steel rings tilted off axis were spot welded to these same inserts and arranged in a balanced pattern. This helped by about a factor of three but the data were far from quantitative. Well it happened that the machine ended up at Los Alamos, where the electrostatic portion was rebuilt in 1943 and in its best days this machine went up to 2.7 MV. The tube was 26 insulator gaps long with the modules being 2.525" long. This machine with the same tube was retired from service last year and at that time it was still good for 2.0 MV. At this point it would appear that I have made a good testimonial for the "inclined field tube." I certainly do not wish to imply that it doesn't have value as a means of getting high gradient. I just believe we can do much better.

The Los Alamos Vertical Generator

Figure 2 is a drawing of the vertical Los Alamos generator.¹ The insulating column of this machine is 20 feet long. The unique feature of this machine is the gas tight separation column so the majority of the tank remains pumped up for years at a time yet access to the high potential apparatus is usually made within 45 minutes. There are several advantages of this construction, however, one disadvantage that concerns the designer of an acceleration tube is the high

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1. For more details see AECD-2038 (1948).

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capacitance or energy storage that the tube must withstand. The capacitance between interpotential shells reading from the inside towards the outside is 560, 1100, 900, 1050, and 1900 μf with the liner shell having 7000 μf to ground.

The author decided in 1948 to use flat electrodes of the aluminum alloy 2024 with the metal rings being $1/8$ " thick cemented between insulating rings of glass-bonded mica $3/8$ " thick. The cemented tube sections were essentially $22\frac{1}{2}$ " long and they join to each other in a 2" space. Two sizes were built, one that had $7\frac{1}{2}$ " to $8\frac{1}{2}$ " ID aluminum rings and the others were $5\frac{1}{2}$ " to $6\frac{1}{2}$ " ID. The inside diameter was graded in 5 steps in each of the 10 sections which were all alike. Now as shown in my other paper, the loading takes place between the ends and not between the rings on a flat electrode tube unlike most tubes with dished electrodes. I believe this is the reason we have found back-biasing effective and almost everybody else has not found it particularly effective.

It is clear that we have a superb machine needing a much better tube, one that has a voltage capability much greater than the 8 MV that we can get with our present tube. We have not had a tank spark in years. There has been difficulty with resistor performance but that has been cleared up. So I have been wondering about a new tube for the machine. It also happens that the dimensions do not correspond to that of a standard HVEC inclined field tube.

Discharge Mechanism

Before reviewing our experiences with back-biased tubes, I would like to briefly state my idea of the discharge processes that apparently take place on the inside of accelerating tubes. I believe we have all seen considerable evidence for most of these processes so let me enumerate them.

First let us divide them into: A) continuous discharge, B) pulsed or kicking discharges, and C) sparks.

Under continuous discharge we have: A1) field emission of electrons and ions, A2) electron or ion release by the operating ion beam in the residual vacuum gas, and A3) ion exchange loading. Pulsed discharges or kicks occur from: B1) ion exchange loading, B2) gas multiplication, and B3) clump or pellet bombardment. Sparks pass through or along: C1) the inside of the tube, C2) the electrode edges of the tube, C3) the insulators, and C4) the protective spark gaps.

Thus there are a number of possibilities to distinguish between and it is not surprising that we disagree some as to what is most important. In a clean tube constructed with good technique I do not believe clumps are important. Neither do I believe photons are important inside tubes. X-rays associated with A2 can be troublesome but we have not noticed trouble in our vertical machine due to the ion chamber effect since the separation column gives shielding.

Ion exchange loading seems to be frequently pulsed and often triggers sparks. This may be because the electrons associated with the loading make many near elastic collisions and end up as charge on insulators. In our test generator we noticed that central sparks are often followed by insulator sparks. The later are

2. This material is sold under the trade names of Mykroy and Micalox.

easy to recognize. They don't make penetrating x-rays as can be told by using an ionization chamber which can sense x-ray pulses. They are exceedingly rapid. Surges from the insulator sparks do spectacular things for they bypass any slightly inductive paths.

The extreme rapidity of the discharge along insulators is easy to explain. Just observe theoretically how that a spark getting started in the central part of the tube can't develop rapidly because of space charge limitation. But for a spark along the insulator there is no space charge problem as charge is immediately available from the insulator surface. For the same reason, it is easy to see how that a spark can develop along the interior edges of the electrodes much more rapidly than through the open center.

It is therefore important that the electrons originating with the ion beam, ion exchange loading, field emission, surface bombardment by clumps, or any other source be trapped in a manner that does not lead to the charging of nearby insulators. It is also quite important that there be no field emitting points adjacent to the insulator and that the insulators join continuously and completely to a smooth electrode.

I believe that the most needed development in the accelerator tube art is a good resistive coating or even an insulator with uniform volume conductivity. If we had that, we would find that many tubes could be conditioned to support quite high voltages. When I discuss the tests on tube F, it will be also evident that perhaps a tougher metal than aluminum is also needed for the electrodes.

Tube A

Our first tube in our machine was the $7\frac{1}{2}$ "- $8\frac{1}{2}$ " ID one as seen in Fig. 1 of my other paper. Figure 3 is a photograph showing the tube in place in 1950. We started with 2 sections, then 4, and finally 6 sections of this tube. Six sections, which made us 12 feet of column, produced reliable operation to 4.2 MV. One trouble in these tubes was manifest in damage to the aluminum electrodes on the inside edge. Fortunately these damaged areas did not extend all the way to the insulator. Since we thought the damaged areas were produced by heavy particles and we had trouble with sparks without warning, we put in diaphragms at alternate 2 foot levels.

We had difficulty with two sections of this tube which were made with high strength porcelain. These became badly punctured and we had to take them out. We have never had a glass-bonded mica ring to puncture. The belt hour meter read 3100 hours when this tube was taken out after 3 years of use in its three lengths.

Tube B

In August 1953 we stacked our column to 20 feet and installed a tube made by HVEC. This was not their standard tube for the modular spacing was increased from 1.0" to 1.5" to match our column. In Fig. 4, a drawing of a typical section of this tube can be seen. We also switched to mercury diffusion pumps and liquid nitrogen traps for this tube. This was their tapered design whereby

the electrodes were 5" ID on the ends and 3" ID a little above the middle. This tube took data at 6.85 MV at first but did not hold up well. In addition it gave us a lot of trouble with beam shifting. A shift would happen suddenly ever now and then. The beam shifting was cured by placing a diaphragm 4 feet from the top that had a 7/8" hole in it and this diaphragm is shown in Fig. 4. It was necessary to back-bias it on the top side, however, to stop the shifting. This to me means that we broke up some sort of discharge on the top 4 feet of the tube that was charging the insulators. Unfortunately the tube continued to deteriorate so we took it out in March 1955 when it was only good for 4.5 MV. During this period of 1.5 years it had been used 3250 hours. Figure 5 is a photograph of a 2 foot long section of the tube in place in the inner column and Fig. 6 is an exterior view of a damaged area in this tube. Post mortem examination showed many bad areas along the insulators where the aluminum from the adjacent electrode had been evaporated or sputtered upon the glass. The larger gap of 1.5" instead of 1.0" coupled with the higher capacitance machine is in my opinion responsible for this trouble. However, there were other possible causes of the rapid deterioration such as trouble with our potential distribution system. Maybe we got more dust in the tube than it will tolerate. At any rate it appeared to be the least rugged of the tubes we tried.

Tube C

The next tube, Fig. 7, was like the tube A except we used the smaller electrodes having $5\frac{1}{2}$ " to $6\frac{1}{2}$ " ID in 5 gradations. This tube was cemented with AYAT vinylacetate as was the HVEX tube and all subsequent tubes. The fillets were smooth and clear and so were left on. Diaphragms having 1" central holes were installed at essentially every other junction as can be seen from Fig. 7. This tube in its initial form went to 6.25 MV but 5.5 MV was about top for it. It had a tendency to spark without warning. In September 1955 resistors of 500 megohms each were put directly upon the tube so the potential of all the electrodes was made definite. This made an important change. Now the loading threshold could be sensed by an x-ray detector on top of the tank as a fair amount of this current could be sustained before it would spark. Apparently the floating electrodes were charging up and initiating sparks before the resistors were installed.

Experiments³ were soon made after the installation of the complete resistor system on the proper bias for the tube as shown in Fig. 7. The loading threshold was for 0 bias - 3.5 MV, for 0.16 of a step bias - 3.3 MV, for 0.21 - 4.2 MV, for 0.33 - 7.7 MV and for 0.75 - 5.8 MV. In spite of the 7.7 MV threshold this tube actually did not operate appreciably above 7 MV. It was removed from use on April 14, 1959 after 4.1 years of service amounting to 9300 hours. I noted in the log book at that time that it would operate at 6.0 MV but could be coaxed up to 6.5 MV. The vinylacetate fillets had been fried to a crisp and also there were many fragments of adhesive over the diaphragms, etc. There were a few white areas on the inside of the aluminum electrodes as were present on the first tube yet I think it is fair to say that this tube only deteriorated from being a 7.0 MV tube to a 6.0 MV tube.

3. See J. L. McKibben, Bull. Am. Phys. Soc. VI, #1, U11 (1956).

Tube D

After the poor performance of our initial tube followed by that of tube B, our Division Leader became concerned. He organized a series of "ad hoc" committee meetings on vacuum breakdown. This was kicked off by a meeting of a number of experts, several present in this audience, at Los Alamos on June 13-14, 1955. This meeting was followed by some 15 meetings of the committee. I was under considerable pressure to try many diaphragms as advocated by Cranberg⁴ and others. Unfortunately, the steps in our tube faced downward so putting in the diaphragms presented quite a problem. I believed that the severe limitations in pumping speed would be a bad mistake especially with the vinylacetate adhesive. On August 1956 I proposed the tube as shown in Fig. 8. Unfortunately, it turned out to be a poor tube in the test generator as it sparked too easily. The design was changed to that of Fig. 9 which should have had less field emission. Also the insulators surface treatment was suspect so they were sandblasted with clean 100 mesh aluminum oxide grit. The new arrangement was coaxed in the test generator to 1.7 MV. However, it was noticed that a few silent kicks producing x-rays would be followed by a rapid spark that made no x-rays. After that it wouldn't hold 1.4 MV for some time. The complete tube of this construction was installed in May 1959. We unfortunately made changes in our ion optical system because we also installed equipment to pulse the ion beam in the terminal at that time. It was some time before we got a satisfactory control of the machine focus potential. And our resistor current readings were not reliable at high values because of a peculiar leakage we have only recently come to understand. However, looking back I see that it had been coaxed to 5.9 MV but that 5.5 MV was essentially the top voltage at which appreciable data had been taken. It was taken out 1 year after installation with 1880 belt hours.

It is worthwhile to point out what I now believe we missed in designing this tube. We overlooked electron charging of the insulator. The straight sided insulator did not provide the impedance to the surge front that the contoured insulator did. We had had considerable mechanical and vacuum troubles with the contoured insulators but they resisted sparking better. Also the outside edges of the diaphragms at the junction of sections were probably a source of field emitted electrons that got scattered into the insulator. That is why the tube of Fig. 9 worked out better in the test generator. In the big machine this tube gave essentially no trouble with ion exchange loading but it sure liked to spark. It was working with these sections that I became much more conscious of the problem of charging of the insulator by electrons and in fact it was while testing this tube that we performed an experiment that showed how a small field emitting point near an insulator could drastically reduce its holding off voltage. Also it should be pointed out that the sections in the high capacitance region of our machine did the poorest with this tube. Finally the insulators of this tube had a large amount of synthetic mica in them. It is possible that the natural mica had enough conductivity to be better. However, our tests with samples did not resolve this point.

4. See article on "Small-Aperture Diaphragms in Ion-Accelerator Tubes," L. Cranberg and J. B. Henshall, J. Appl. Phys. 30, 708 (1959). Incidentally the correct voltage values are obtained by multiplying the published values by 0.68 for the reasons explained in my other paper.

Tube E

When it was realized that tube D was doing poorly, it was decided to put back tube C. Five small changes were made, however. 1) We used the diaphragm of Fig. 10. This had better rounded surfaces. They also had 5/8" central holes instead of 1" holes and were also made of steel. 2) These diaphragms were placed at every junction instead of every other junction. 3) The tubes were dismantled, the electrodes were repolished, the rings were resandblasted with 100 mesh aluminum oxide grit, and it was more carefully jigged for alignment. However, this time we washed the fillets away with acetone followed by alcohol rinse and oven drying back in the jig. 4) Three sets of spark gaps were put on the outside. These were made from 5/8" stainless steel balls with 0.10" gap. They can be seen in Figs. 11 and 12. Note that the light from one spark illuminates its neighbor. And it is clear that they do get used as can be seen by the discoloration in the gaps. 5) A 400 l/s sputter pump was added for pumping.

This tube was installed in May 1960 and now 4.5 years and 8100 hours of service it is about as good a tube as new. It will operate at 7.5 Mv dependably and with coaxing to 8.5. At one time it delivered ions of 9.25 MeV. Some of our troubles have been resistors, belts, blower tube, etc. but that is another story and one upon which we have made considerable progress.

The pumping speed was measured at 33 l/s for the tube, 210 l/s for our mercury pump and trap, 360 but rapidly dropping to 270 l/s for the sputter pump, and 525 l/s for the combination measured at a flow of 8 atm cm³/hour of air. The ultimate vacuum was 1.4×10^{-6} Torr at the base of the tube and 5.4×10^{-6} Torr at the top of the tube as measured by Veeco ionization gauges.

Over the past 4½ years we have kept the sputter pump running in parallel to the mercury pump and trap. I have a belief that the tube works best for the combination but have no solid evidence to back up the belief so it may only be a superstition. The sputter pump will not handle the tube alone for a spark will overload it.

Voltage breakdown trouble with this tube shows up first at the top end. Sparks occur here. Since the machine has pretty quick recovery for sparks in either of the top two sections the operator is often not as aware as he should be of sparks occurring here. Eventually sparks will occur that take the voltage of the machine to zero if too frequent sparking in the top part is allowed to persist. There is a warning that can be sensed by an x-ray scintillator mounted on top of the tank where at 12 feet from the source and through about 4-5 inches of steel it still can sense x-rays associated with the discharges. Unfortunately however, even a one microampere beam releases electrons that make enough x-rays to pretty well mask out tube x-rays associated with discharges in the tube so it is not very helpful except for diagnostic testing.

Tests on Single Sections - Tube F

At the time we were considering what tube E should be, I proposed that we try a tube as shown in Fig. 13, but the need to be sure that we had an

operating tube of a certain minimum quality caused it to not be tried. However, we did spend a month running some tests on a single section mounted at the usual position at the bottom of the column, see Fig. 2, and most of the work was on the tube of Fig. 13. The voltage was measured on a separate string of resistors that did not connect to the column except at the top of the section. The resistors were 300 megohm helical carbon film rated at $7\frac{1}{2}$ kV each in air but they were carefully measured by our standards laboratory at 3 kV and 20 kV with the resistance at 20 kV being about 90% of that at 3 kV. They were assembled on the column structure visible in Fig. 5. The structure is in the notch to the right of the tube but was located during the test work in a much larger notch not visible in the photograph.

To make the test more worthwhile, we used 4 channels of recorders. These followed the voltmeter resistor current, the ion gauge, an x-ray sensing ionization chamber connected to a vibrating reed electrometer, and the current to the bottom diaphragm plate. In some cases the resistor current on the tube was used instead of the current to the diaphragm. These records did prove very instructive to diagnosing what might be happening inside the tube and we should have done the same with our test generator work earlier.

To find out more about the effect of the capacitance, we had a resistor chain of 4000 megohms to the big shell which has 1900 μf capacitance. These resistors could be shorted out by a 1/16" cable that was operable from outside of the tank. The back-bias voltage at the bottom was from an external supply. The top back-bias could be taken out by this same cable.

Most of the tests were on the section of Fig. 13. Steel terminating plates as shown were used on one test and aluminum terminating plates were used on another run. The steel plates had a lower threshold voltage for ion chain loading. With zero bias, the ion chain loading threshold varied from 0.36 MV to 0.78 MV depending upon the metal and the amount of conditioning. A bias voltage of 5-8 kV on one end would raise the voltage to the range 1.1 to 1.3 MV where it would spark rather than load. These sparks usually came without warning. They seem to propagate along the interior edges of the aluminum electrodes. Since we used the same spark gap system as can be seen in Fig. 12 which has 3 rows of balls with 0.10 inch setting, much of the sparking may have transferred into these gaps. These sparks seldom dropped the voltage down more than one third unless the cable bypassed the resistors to the big shell when the voltage went to zero.

The tendency of the tube to spark along the interior edges seems to be different than we observed in the test generator where we believe the fast sparks in the tube were along the insulators. There the head capacitance was 60 μf instead of 1900 μf and the hoop to hoop capacitance was 90 μf instead of 1050 μf . Sparks often occurred in the test generator with no detectable x-ray output and we did not use any spark gap protection in it except for the resistor holders which were as can be seen in Fig. 12. The voltage in the test generator that corresponded to 1.3 MV on this tube section was I believe about 1.6 MV. But in the test generator the insulators developed lines along them due to surface flashover. In the big machine these lines did not develop to any appreciable extent. But the interior edges of electrodes did get torn up and radial line distribution of small droplets of aluminum

did appear on the terminating plates. Also these sparks usually did have an x-ray pulse associated but it was no larger than some pulses described below which did not lower the voltage more than 8%.

We wanted to determine the ruggedness of a tube section with respect to many sparks and what the deleterious effect of mercury vapor might be on the tube. The tube was allowed to spark some 500 times with the 1900 μmf shell connected. About 100 of these sparks were made with the liquid nitrogen trap warmed to near room temperature so the mercury vapor pressure read as high as 4×10^{-7} Torr. for 20 hours. This had no appreciably bad effect except for slightly lowering the threshold for ion exchange loading as was noted when the bias voltage was turned off. In fact there was a beneficial effect of the treatment as explained in the next paragraph.

After awhile in this test we noticed that frequently a very peculiar event took place. The voltmeter resistor current would show a sharp downward spike with less than 2% step change in value as if a surge was capacitively coupled from the top. A sharp spike would also appear in the ion gauge even with its filament turned off. There was a spike also coupled to the x-ray ionization chamber which looked up the tube through a glass window. The spike was followed by an x-ray pulse. I believe the event was caused by a droplet striking the top plate and giving rise to a burst of positive ions. These ions were space charge limited so before the secondary electrons had a chance to return the little hot emitting spot had cooled off and there was no spark. Now the interesting thing about the exposure to the mercury vapor was that this type of breakdown ceased. In fact the tube section seemed to hold the voltage of 1.2 MV with a low sparking rate of once every few minutes. Thus I find myself believing that the mercury vapor cemented the droplets to the plate.

A section of tube E was tested a little while in this setup. It behaved in a somewhat similar manner but not quite as good. After the test, I wrote in the monthly progress report "that it should operate to about 0.9 MV/section in agreement with previous experience." And that the section described above "might be expected to operate near 1.1 MV satisfactorily." The previous experience was the first version of tube E or tube C and the value has turned out to be a pretty good value.

Conclusion

The best summation that could be given to the above would be a prescription for a better tube. Obviously, I still can only guess. I find myself believing that we should use stainless steel for electrode material. Denholm has found it to be good and its ruggedness might break up that inner edge discharge. It might be not so good about ion exchange loading as buffed aluminum but it can be gotten clean. I have some 316 with extra low carbon in 1/8" sheet with an eight micro inch finish on both sides. There is also an electropolishing technique which will take it down to a one or two micro inch finish. The same electropolishing technique is used to prepare stainless steel for ultra high vacuum so it should remove sources of negative ions. Anyway back-biasing can take care of that problem -- if we can fix the edges and insulators so as to hold more voltage. I believe we can go to a much higher gradient even in the high capacitance machine we have at Los Alamos.

This report covers a large amount of work by many people over a period of better than 15 years and so it is impossible at this place to give proper recognition to their work. We are especially indebted to Richard K. Beauchamp who has been with me on the entire project and who has worked out to perfection details in cementing jigging, and washing. Robert Luders and Dennis Lamb have done most of the polishing of electrodes and assembly and I am convinced that this careful workmanship has had a lot to do with our success. James Henshall and Ralph Nobles in testing have made valuable contributions.

ADDED NOTE

I would like to call your attention to the report of J. W. Mather and A. H. Williams on "Some Properties of a Graded Vacuum Spark Gap," R.S.I. 31 297 (1960). This is quite a successful vacuum spark gap which passes very large currents and yet will hold off 30 kV so it involves problems of common interest although their conditions are extremely different. The vacuum must not be too hard for proper triggering and inductance and so they normally have a small air leak for this purpose. They do find that organic contamination is bad. It is interesting that they have found brass to be the ideal electrode material. Perhaps this is because it can stand the enormous amount of sputtering and resputtering that goes on between the electrodes without becoming badly corroded or does not become rough due to crystal growth or jet formation. I therefore wonder if their experience bears upon the problem of breakdown along the edges. Furthermore, Mather at present is very much interested in the fact that copper seems to form crystals in the crevices in the glass and seems to provide a potential distribution over its surface. Since a single gap shows current and kicks in the 25-50 kV range, it cannot be said to have been demonstrated as helpful at high voltage gradients but it is interesting.

FIG. 1. Drawing of the first accelerating tube made by the author with R. L. Burling and under the guidance of R. G. Herb at the University of Wisconsin in 1939. This was used in the "short tank" that went to Los Alamos in 1943 and was finally retired in 1963. Note the spun steel electrodes and the heavily convoluted porcelain rings. The vacuum seals were made using 0.010" sheet rubber. The tube was horizontal and 26 gaps in length.

Fig. 2. Drawing showing many of the features of this machine built 1949-50. The separation column permits the large outer region of 5000 cu. ft. to remain pressurized with 150-250 psi air for years at a time. Access to the inner region is by decompression of the small inner volume of 300 cu. ft. and by hoisting tank with the 150 ton crane making access to the high potential apparatus within 45 minutes. The inside diameter of the liner shell is 12 feet and the insulating column is 20 feet long with 5 more feet for the apparatus. The top voltage of the basic machine is as yet unknown but over 10 MV.

Fig. 3. Photograph made in 1951 of the machine with a column stacked 12 foot high. Tube A was in place then. Two sections were made using type AB2 porcelain. The acrylic tube in the center of the column is used to blow cooled nitrogen to the top of the column. One side of the service platform was opened for a better view of the head and bottom of the tank. A few rings of the separation column are visible through the hole in the bottom of the tank.

Fig. 4. Drawing showing electrode and insulator shape of tube made by High Voltage Engineering Co. The diaphragm was added by us at a position 4 feet from the top and the potential distribution required with it was as indicated.

Fig. 5. Shows tube B or the HVEC fabricated tube in place in the 13 inch notch in the inner column. The column has a 1.5 inch modular spacing while their standard tube has a 1.0 inch modular spacing. The rubber connectors they used at that time are visible as well as two of the three rows of spark gaps. Potential distribution was by resistors not visible although the movable column on which the adjustable corona system was mounted is visible to the right of the center of the picture.

Fig. 6. Closeup of tube B showing two damaged rings of the HVEC tube. The damaged areas are indicated by arrows and show through the insulators which were Corning 7070 glass. One of the rubber connectors has been removed for the photograph. Examination of the interior showed that aluminum had been sputtered and jetted upon the glass from the adjacent electrode.

Fig. 7. Tube C installed April 1955 was like tube A except 2 inches smaller in diameter. The joining flanges between the 2 foot long sections were also new from that used in tube A. Diaphragms as shown were used at every other junction except for the extra diaphragm 2 feet from the top. Back-bias potentials as obtained from the resistor system are indicated with respect to potential V in unit steps, the voltage across a $1\frac{1}{2}$ " step being regarded as a unit. The inside diameters of the flat electrodes were $7\frac{1}{2}$ ", $7\frac{3}{4}$ ", 8", $8\frac{1}{4}$ ", $8\frac{1}{2}$ ".

Fig. 8. Suggested design for tube D. This was abandoned when the test of the first section in the test generator showed that it had a strong tendency to spark.

Fig. 9. Tube D as installed in May 1959 for one year. Several areas with field concentration have been removed. This tube was used only to 5.5 MV for the full ten section length yet a single section as shown had been worked up to 1.6 MV in the test generator. The straight sided insulators were probably the worst mistake we made on this tube but the field emitted electrons from the diaphragm no doubt tend to charge these insulators.

Fig. 10. Diaphragm as in use in tube E which is similar to that shown in Fig. 7. This tube also appears in the photographs of Figs. 11 and 12. The single sections appear to hold 0.9-1.0 MV and the 10 section tube operates up to 8.5 MV. The diaphragms were made of steel. The flat electrodes $10\frac{1}{2}$ " OD were 2024 aluminum alloy. The ceramic rings were Mykroy 38. The adhesive was AYAT vinylacetate and the fillets were washed away on the interior with acetone. It is probably quite significant that most of the sparking is in the top two sections. There has been no apparent depreciation in the top operating voltage since its installation $4\frac{1}{2}$ years ago.

Fig. 11. Photograph made in Sept. 1964 showing the top of tube E and the terminal apparatus. The new ion source that puts out negative ions as well as positive ions is on top of this tube. Reversal of polarity is accomplished by 3 motor driven reversing switches without opening the tank. Thus the tube now needs to work well with negative as well as positive polarity.

Fig. 12. Closeup of tube E showing its hardware. The balls on the end of flat springs make contact from the inner column to the separation column. The connection from the tube to the inner column is made by the spring connectors visible on the right side of the tube. There are 500 megohm resistors across each gap of the tube and these resistors are of type HBM but made on solid rather than tubular porcelain. They are mounted in three columns because with the shields they could not be located closer apart than every third ring. And there are also 3 columns of spark gaps, one of which is in the center of the tube as presented.

Fig. 13. Tube section F tested as a single section in the big vertical electrostatic generator in 1960. This would hold 1.1 MV for several minutes at a time and for short times 1.3 MV. This tube would hold about 0.3 MV higher voltage in the test generator where the capacitance was at least an order of magnitude lower. The electrodes marked C were used during part of the test and perhaps helped. Electrodes A and B were aluminum in part of the tests, steel in part of the tests, and electrode C as well as all the flat electrodes were aluminum.