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Magnetic Analysis of Ions Involved in Current Leaking at 700 kV*

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MASTER

I. Introduction

This is a summary of work, unpublished except in abstract form, on ion exchange loading and results of magnetic analysis of the ions made with the hope that it might show what is happening. Several other diagnostic tests will be discussed. This work came about as the result of our work in development of ion-accelerating tubes. In the opinion of the author it leads to the conclusion that the loading is a multiplicative sputtering process sustained by the positive and negatively charged ion components. It also leads to the conclusion that electrons, while carrying about 98% of the current, are not important in sustaining the process. Of course the by-products of the discharge in the form of electrons produce x-rays which affect the environs of the machine and may in addition give rise to the ion chamber effect noticed by C. Turner. In addition the scattered electrons place charge on the insulators leading into insulator flashover on the vacuum side.

In considering this paper, I found that to make the story complete, it was necessary to review work done in this laboratory even 14 years ago. Unfortunately, I have been remiss in my publication responsibility. Also, I have included other material from our tests that I hope will help to verify my thesis that the basic mechanism involves chiefly negative ions from one surface and positive ions from the other surface in the accelerating tubes with which we have worked. In the meantime several other people have worked and published on this problem. Unfortunately, the short time available to me in the writing of these two papers has not allowed any appreciable searching in the literature. The references I shall include were ones that could have and perhaps did affect our work and none are later than 1959.

Probably the first people to observe the multiplicative loading process were Van Atta, Van de Graaff, and Barton¹ in an 0.3 MV accelerating tube 53 cm long. They seem to have suspected they might have a multiplicative process "at the electrode surfaces because of the impacts of ions, electrons and photons." They then effectively said that the sum of the products of the multiplicative coefficients must equal unity for the discharge to proceed. However, they did not mention negative ions and they did not distinguish

* Work performed under the auspices of the U. S. Atomic Energy Commission.

1. See Van Atta, Van de Graaff, and Barton, "A New Design for a High-Voltage Discharge Tube", Phys. Rev. 43, 158 (1933).

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between the breakdowns they had and the continuous current. It is also interesting that they did suggest that grids might be useful. This was followed by a classic paper by Trump and Van de Graaff² in which the magnitude of the coefficients were measured and found insufficient. We still seem to be faced by that dilemma. My chief criticism of this paper is that it also did not distinguish between continuous discharge and sparks or "breakdown" as they called it yet they were using the criteria of a continuous discharge.

Early independent observations of the continuous effect were made by C. M. Turner and J. P. Blewett.³ Turner also made his observations in an accelerating tube and he observed the sharp threshold voltage and the increase of this threshold voltage with tube pressure. The technique of making accelerating tubes was much improved by then and his observations were more distinct. Blewett made experiments on short gaps and tried to explain it as an effect noticed by Malter. Early observations on the effect were also made in France by Bruck and Prevot.⁴ The work of Arnal⁵ is interesting and extensive but, by using fluorescence as the sensing device, his mass distribution and conclusion is quite wrong. The work at Washington University on spheres charged in vacuum by radioactive sources under the direction of the late Joseph Kennedy⁶ is quite interesting especially since they worked with tiny charging currents and also because their approach was as chemists. I note that they too came to the conclusion that at least part of the picture is an exchange of positive ions and negative ions. Leland and Olson⁷ at the Los Alamos Scientific Laboratory made measurements at our suggestion. The spectra they got are very much like what we see, however, the coefficients they obtained are low at almost an order of magnitude.

Gyftopoulos⁸ working in Trump's laboratory at the Massachusetts Institute of Technology has also made magnetic analysis of the ions. However, he tries to make the point that negative ions are formed in a gas layer in front of the cathode surface. This concept I find difficult to believe since the threshold is very sharp and definite and therefore how can a gas layer have anything to do with its initiation. However, as the exchange process starts, neutral material is sputtered out and this can

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2. See John G. Trump and R. J. Van de Graaff, "The Insulation of High Voltages in Vacuum," J. Appl. Phys. 18, 327 (1946).
 3. See C. M. Turner I⁴, and also J. P. Blewett I⁵, Phys. Rev. 81, 305A (1956).
 4. See H. Bruck and F. Prevot, Rapport C.E.A. No. 189, Centre d'Etudes Nucleaires, Saclay (1953).
 5. See Robert Arnal, Annales de Physique S12, V10, 820-873 (1955). A Consultant's Bureau, New York 11, translation is available under code #CL 16410.
 6. See Kennedy, Bryant, Merten, Murphy, and Storms on "Some Experiments on Electrical Conductivity in Vacuum," AECU-3989 (1957).
 7. See W. T. Leland and Roy Olson on "The Production of Ions at Metallic Surfaces Bombarded by Energetic Ions," LA-2344 (1959). Also see Bull. Am. Phys. Soc. 1, #8, R5 (1956).
 8. See Elias P. Gyftopoulos' unpublished paper entitled "Electrical Processes in High Vacuum Acceleration Tubes." (1958)

effect the multiplication and in section V I shall cite an example we found. The contribution to the multiplicative process by the neutral material in the gap might be expected to cause the discharge to be pulsed. Sometimes we did see strong pulses or kicks but I have the belief that we were working with continuous discharge in much of our work in the test generator. Unfortunately, I find that our recorded data is not sufficiently complete to definitely prove it and the apparatus has been dismantled. It did show that the size of pulses or kicks depends upon conditions. I know I have had the belief that the discharge was often continuous for many years.

Now one thing above everything else that we should do at this conference is to come to an agreement on a name for this process. Our secretary, in listing our program, could not read my title as I had it written in long hand and changed current loading to current leaking. I don't blame him, in fact current leaking may be a more descriptive name and so I have let it stand in the title of this paper. My preference is to call it ion exchange loading but have used several names in this paper. There are several other kinds of loading that takes place in accelerating tubes so one uses the term ion exchange loading for this particular form of loading. Gyftopoulos has suggested pulsed discharge but the discharge is not necessarily pulsed. The name dark current has been used for some time. Bertein and Arnal have suggested the name micro-discharges, however, a name more descriptive of the mechanism involved seems desirable. Most physicists are not aware of this process, but since we have neither an explanation nor a good name agreeable to everybody then this must be expected.

II. 1950 Tests

While we⁹ had studied the process involved in breakdown in vacuum since 1946 at Los Alamos, my first good observation on the process was January 1950 with the assistance of R. K. Beauchamp when we first studied the discharge process in an accelerating tube section in our test generator. It seemed to me very significant that the voltage at which this process would take place⁴ could be increased by either spoiling the vacuum to pressures of around 10^{-4} Torr. or by insulating the top plate. The tests were made on the tube section and in the machine shown in Fig. 1 except that the top plate was a simple insulated brass plate. The bias voltage required on the top plate was about what was needed to prevent low energy particles emerging from the plate from passing through the potential saddle and thereby being accelerated into the bottom end of the tube.

A series of three measurements made in cooperation with Keith Boyer¹⁰ in November 1950 clinched my belief in the exchange of negative ions and positive ions as the basis of the continuous discharge. (While editing this paper, I discovered with interest that I had mentioned both the possibility of negative ions being involved and "chain reaction process" in my 1948 paper.⁹) First, as in Fig. 1, a filament was mounted in the top plate and

9. J. L. McKibben and R. K. Beauchamp, "Insulation Flashover Tests in Vacuum and Pressure," AECD-2039 (June 1948).

10. J. L. McKibben and Keith Boyer, Phys. Rev. 82, 315A (1951).

the secondary current back to it was measured. We got a value of 1.2×10^{-4} for the positive particles per electron and this was constant for energies of 0.7 to 1.4 MeV. This value was about 16 times smaller than that of Trump and Van de Graaff.²

Next Boyer and I showed that the returning electrons did not appreciably contribute to the discharge mechanism by the arrangement in Fig. 2 where, with suitable choice of potentials, the secondary particles from the top plate could be focused on the bottom plate. However, a leak increasing the pressure to 3×10^{-5} Torr stopped the discharge so that the voltage was limited by sparking in the region external to the tube or along the vacuum side of the insulators of the tube. The presence of the loading could be ascertained by meters to the top plate and to the screen lining the acrylic tube. The loading also showed up by the x-rays, unless a small magnet was brought up when the x-rays disappeared. However, the loading threshold voltage stayed the same and was now manifest by a current through meter B of a value up to 10 μ A. One could also easily see where the magnetically deflected electrons struck the plastic tube. The spot where the positive ions struck the top plate was also visible but as a quite faint glow. The ratio, meter B to A, gave us the ratio of electron current to the total ion current and was 50 in fair agreement with later results.

The third experiment of Boyer and myself is shown in Fig. 3. Here we were able to get the positive ion beam focused on a 0.05 inch wide slit and to apply magnetic analysis to what came through the slit. The unfocused spots of different masses were seen on a fluorescent screen at the top of the analyser box. The two masses of hydrogen were clear, there was some faint luminosity near mass 12, and we had an argument as to whether we saw anything heavier. No doubt iron from the bottom plate was present but it didn't fluoresce. The experiment, however, did give us a calibration of our generating voltmeter through the calibration of the magnet and this was checked by observing the energy at which protons came through a foil of aluminum. Our highest obtainable voltage was 1.7 MV for this tube even with the top plate properly biased and the limit was tube and machine sparks.

These experiments were crude. The vacuum system was oil pumped and we had to use liquid nitrogen to get even down to 1×10^{-5} Torr. But the use of the 8 inch inside diameter tube gave us an advantage. Somehow these experiments worked out well and it is too bad they have not been more carefully repeated.

One point about our experiments on ion exchange loading is that the process seems to take place entirely between the end surfaces and does not involve the intermediate electrodes as in the usual accelerating tube which does not have flat electrodes of large inside diameter. Gyftopoulos⁸ saw ions from various "weak" electrodes in his tube. Our open geometry has a big advantage for it does appear that essentially all the ions leave the surfaces at low velocities and so the electrostatic field determines the possible trajectories between the end plates.

III. 1956 Mass Analysis Test

In the fall of 1956 James Henshall¹¹ and myself worked out the experiment shown in Fig. 4. The accelerating tube section had electrodes varying from

11. J. L. McKibben and James Henshall, Bull. Am. Phys. Soc. 1, #8, R4 (1956).

$5\frac{1}{2}$ inches to $6\frac{1}{2}$ inches inside diameter instead of a $7\frac{1}{2}$ inches to $8\frac{1}{2}$ inches inside diameter as in the tube of the previous tests. The tube was 39 gaps in active length with each insulating gap being $\frac{3}{8}$ inches high between $\frac{1}{8}$ inch thick 2024 aluminum alloy plates. The system was mercury vapor pumped and liquid nitrogen trapped. The vacuum was about 2×10^{-6} Torr. The tube had 39 of RPC's BBM resistors of value 1 K megohms each to distribute the potential. We found that a plate at the top of the accelerating tube section which reduced the field concentration on the end electrode seemed to be a good thing and was used on the tube in this test. It was given a slightly conical shape so as to throw the secondary particles towards the middle and away from the electrodes.

The beam of ions that came out of the 1 inch hole in this terminating plate of the tube was focused by an electrostatic quadrupole lens onto the plate at the extreme top end of the vacuum system in Fig. 4 which was either a glass plate covered with zinc sulfide or a slit cup assembly. An electromagnet was used to deflect the ions by 15.3° so they were separated into their mass-per-unit-charge components. As the voltage on the tube was turned up nothing was seen on the fluorescent plate until the loading threshold was reached when a series of lines became visible.

The mass distribution of the ions was determined with an automatic plotter. To get this distribution the field strength of the magnet was swept from zero to the top value in a period of two minutes or so, while the dark current was present in the tube. The field strength was continuously measured by a rotating fluxmeter, its output was squared, was divided by the value of voltage as indicated by the generating voltmeter, and the resultant signal used to control the abscissa of the plotter. The ordinate was the intensity of the ions as measured by a vibrating reed electrometer through 10^9 ohms.

It was observed, with about $10 \mu\text{A}$ of ion exchange loading current in the tube, that 700 nA of electron current escaped through the top hole and that a total of 15 nA of positive ions were detected in the slit cup and a total of 5 nA of negative ions were detected. The ratio positive to negative current has some significance because the total loading current was held close to $10 \mu\text{A}$ in each case. This indicates that 35 electrons pass across the gap for each ion. However, since the probability of an electron releasing a positive ion has been measured to be 10^{-4} in such a tube with voltage on it, we see that the electron contribution cannot be important to the mechanism that sustains the current. I am assuming that the photoelectric coefficient product is also small. The electrons, however, are important as a carrier of current and are the source of x-rays.

The results of these measurements are shown in Table 1. This table clearly shows that aluminum ions, which in this case were almost twice as intense as hydrogen ions, must be the important positive ions in the process. An important contribution from heavier ions was also taking place. However, when one looked at the fluorescent lines on the ZnS screen the very weak mass three line appeared about as intense as the aluminum ion line. If fluorescence alone is used to detect the ions one is inclined to greatly overemphasize the importance of hydrogen as Arnal did in his paper.⁵

These results suggest that freeing the surface from oxygen and chlorine might greatly increase the voltage. They also suggest that the cleanliness

of the surface could be examined by this technique but unfortunately getting results was not easy with negative ions as the tube in this case had a strong tendency to spark.

IV. 1959 Mass Analysis Test

In 1959 Henshall and I did some work with the tube section shown in Fig. 5. This tube was made with 2024 aluminum for electrodes and with Mykroy 38 convoluted insulators. Note that the electrodes were tapered as can be seen in Fig. 5. The assembly was cemented with AYAT vinylacetate and the surplus adhesive washed away with acetone. The assembly started conditioning at 400 kV and in 5 minutes time went to 1050 kV where it would "silently" spark. Since the inside length of the tube was 6.3 inches, this is a quite high gradient for a one megavolt tube and stresses the insulators to almost 90 kV per ring. (A single gap was taken to 145 kV in another test.) These silent sparks were accompanied with sizeable x-ray pulses which therefore must mean that much of the charge went through the central gap. It had been hoped to do ion exchange loading on the tube, however, to get a continuous discharge the concave electrode shown dotted in the bottom of the drawing of the tube in Fig. 5 had to be introduced. This structure gave loading in the range of 450 to 625 kV, the value depending upon how long it had been operated at a given time. There was trouble with sparking or large discharge pulses at the higher voltages for positive ions and a great deal of trouble even at low voltages for observation of the negative ions.

The analysis of positive ions is shown in Fig. 6 and the negative ions in Fig. 7. Figure 7 is from a lucky run and the focus is not nearly so sharp as for the positive ion run. Getting a good record involved not only correct quadrupole focus and slit opening but also the back-bias voltage on the top electrode terminating the field.

Unfortunately, the fraction of the 10 μ A loading current that appeared in the analyzed beam from the tube of Fig. 5 is down by about a factor of 5 for positive ions and about a factor of 500 for electrons and negative ions in comparison to the tube of Fig. 4. This unfortunately suggests that the majority of the loading was between the outer edge of the concave bottom electrode and the top plate and that only a small part of the discharge struck the center of the concave electrode where the ions sensed in our experiment must have been formed.

Figure 8 is a curve taken from Leland and Olson's⁷ report and shows mass analysis of positive ions created on an aluminum surface of the same alloy when bombarded by 100 keV n_2^+ ions. Unfortunately they did not use a log plot and the Al^+ ion peak is off scale by about a factor of 50. One marked difference is that their $^{27}Al^{++}$ peak at mass 13.5 is not present on our curve but that the mass-per-unit-charge value of 6.75 is present which must mean that the conversion to double charge took place between focusing by the electrostatic lens and the magnetic field. It is interesting that among the several records we took that Al_2^+ seemed to hold closely to the value of 1.2% of the Al^+ peak and that the oxygen compounds of aluminum also held a fairly constant ratio. The contaminants such as hydrogen, sodium, potassium, etc. varied by a factor of three or so. The mass at 18 may be H_2O^+ , at any rate it hardly appears on some records.

Figures 9 and 10 on negative ions are also from Leland and Olson's report.⁷ One was made from a fresh target with considerable organic contamination while the other was made after some considerable bombardment so the contamination is low. It is obvious that our organic contamination was also low but our chlorine contamination was much greater than they had. It does appear that the oxygen contamination of the surface should have an important role in the negative ion output and some results discussed later on magnesium as a cathode surface bear this out.

V. Other Pertinent Tests

One problem that discouraged publication of these results was our voltage scale. This depended upon a chain of type BBM¹² helical-carbon-film resistors in 1 K megohms. Our tests somehow did not show up the strong voltage coefficient present in the resistors and I believe that we confused the 669 keV level in $F(p,\gamma)$ for the much stronger 874 keV when we bombarded a lithium fluoride target by an external ion source. The nuclear reactions were difficult because of the low intensity and the lack of adequate voltage stabilization of the test generator. While I found it extremely frustrating, I was able to go back through the data books and account for most of the errors in our voltage scale and believe that the only consistent one agrees to the energy of the ions as coming from the end plate of the tube. The magnet was calibrated with an aluminum wire that duplicated the ion trajectory and the calibration could be done much more accurately than we could hold the voltage. I have no doubt whatsoever but that the ions came from the end of the tube of Fig. 5 and the sharpness of the mass lines of Fig. 6 certainly attests to this fact. I also have little doubt but that the ions in Table 1 came from the end of the tube of Fig. 4 but why we went wrong on the 874 keV gamma ray level is hard to explain.

The effect of leaking nitrogen into the tube of Fig. 5 was observed. The pressure in the tube was crudely estimated to have been raised from 5×10^{-6} Torr to 5×10^{-5} Torr with an increase of the current leaking threshold from 563 kV to 684 kV. The observed positive ion current decreased by about a factor of 100. No new peak in the mass spectrum showed up, neither at mass 14 nor at mass 28. The tendency of the tube to spark was markedly increased, however.

Another pertinent test on the tube of Fig. 5 was the change in voltage resulting from a change in loading current. At 1 μ A the voltage was 440 kV but at 20 μ A the voltage increased by 9%. At the time of this test it was also observed that the hydrogen line could be faintly seen by fluorescence even 150 kV below threshold and that as the charging current was increased the line moved to a spot where it seemed to stay but got bright by several orders of magnitude.

12. Made by Resistance Products Company. These resistors were tested in 1961 by the standards laboratory at Los Alamos. They will operate at considerable higher voltage than their rated value of $7\frac{1}{2}$ kV with proper corona shields and pressure insulation. Under these circumstances the ratio of resistance value at 30 kV/10 kV is 93% instantaneous value and 88% steady value and the ratio at 50 kV/10 kV is 85% instantaneous value and 76% steady value. The instantaneous value is read immediately upon turning up the voltage while one has to wait until temperature equilibrium has been established to get the steady value. Unfortunately our own tests did not show these large coefficients and I believe that was the reason our voltage scale was off.

Still another pertinent point is that we did some tests in April 1957 on an arrangement of accelerating tube and focus tube that displayed a very interesting shift of loading voltage with the current in the discharge. Unfortunately, I cannot present a good drawing of the arrangement but it is one you are apt to encounter in a usual accelerating tube because it involves a focus tube. Imagine in Fig. 4 that the top terminating plate of the tube had about a 3" central hole and above it a cylinder 4" in diameter and about 14" long. Remove the quadrupole lens and everything above it and cap the vacuum system with a simple insulated plate. At the bushing place a 100 megohm resistor between the lead and the microammeter so the focus tube will be at about $2\frac{1}{2}\%$ of the terminal voltage. Now the threshold was observed to be 950 kV with either positive or negative voltage on the terminal and this was detected both the microammeter connected to the terminating plate and the x-ray monitor. But if the terminal of the generator is made positive it was found that the voltage drooped off as the loading was increased and was 600 kV at about 60 μ A. If the terminal was made negative, the voltage in a similar manner rose and became 1350 kV for about 40 μ A of loading. Now we actually had an ion source installed on the top plate at the time and we had several other problems in mind so unfortunately we did not pick up this important lead. I would like to guess that the effect was due to positive space charge in the focus tube, and that the space charge was positive because electrons escape rapidly. With a positive beam going towards the high potential terminal, this was a defocusing force. With a negative beam going towards the terminal, this was a focusing force. And in addition negative ions formed in the tube tend to be guided out by the space charge so this threshold voltage droops while the tube has the charge present in it and negative ions are coming through it or originating within it. Unfortunately we did not try the effect of poor vacuum in this arrangement. This does show that the increase of the current on the 6th power of the voltage excess reported by Turner³ is not necessarily true.

Another set of pertinent tests were made with heated emitting surfaces of various materials mounted 10 inches above the terminating plate of a similar accelerating tube section to that in Fig. 4. The effect of bias potentials was studied and were large but the heating tests were made with no potential difference. It was found that metals varied and that the effect of heating was quite different especially if they were exposed to a small hydrogen or oxygen pressure of about 1.5×10^{-7} Torr while hot. Materials tested were aluminum, magnesium, titanium, tantalum, molybdenum, and nickel. The most outstanding material as an anode cold or hot was aluminum and it was also a fair cathode material. The most outstanding material as a cathode was magnesium. Cold magnesium was not as good as some other materials but after its temperature was brought up to 375°C for awhile it became outstanding as a cathode material but a little poorer as an anode surface. Cooled to room temperature it was still good as a cathode surface, however, the surface was not stable in this condition and exposure to air or even over the weekend in the vacuum system at 2×10^{-6} Torr lost most of the gain due to heating. However, this result certainly suggests that the contamination and oxide on the surface of the magnesium had a lot to do with the negative ions available and that at 375°C the surface contamination diffused into the material so a clean surface was presented. Nickel was interesting in that at 520°C it was little different hot than cold, but exposed hot to a small hydrogen pressure it became a good cathode material and a poor anode material, and exposed

hot to a small oxygen pressure it became a good anode material and a quite poor cathode material. Also it is noteworthy that the factor between good results and the poor initial results was much greater in general for cathode surfaces than for anode surfaces. Anode surfaces conditioned usually less than 30% except hot in hydrogen it was found that molybdenum, tantalum, and aluminum dropped to about 1/2 of their starting values. Molybdenum also became a very poor anode material in the presence of oxygen. The conditioning factor on cathode materials went as high as 6. This would seem to be in line since the basic metal forms positive ions easily while the negative ions are from the oxides and other contamination and this can be cleaned up. The oxide film in the case of aluminum is more resistant to sputtering than the basic metal so the well buffed oxide film forms fewer positive ions than the clean metal. Other metals also showed this tendency except molybdenum for which oxygen increased the sputtering. Bearing out my interpretation of our results, note that Leland and Olson⁷ found that oxygen pressure of 1×10^{-6} Torr present during bombardment could greatly increase the emission of mass 56 among other masses from their iron target.

VI. Conclusion

I believe as stated in the beginning that this data is best fitted by a multiplicative process whereby positive ions release electrons and negative ions, and that the negative ions rather than the electrons release more positive ions. The summed products of the two coefficients over the various species including the photon effect must exactly equal unity for the process to go at the voltage threshold because of the multiplicative nature of the process. The process has therefore a very sharp threshold. The accumulation of a fair amount of neutral material in the gap especially with a high capacity source can account for a tendency to pulse. This is especially true as space charge comes to play in the process. Of course both of these effects must be greater for a supply of large capacitance which will therefore pulse.

The increase of the threshold with pressure is in my opinion due to the breakup of the negative ions into neutrals and electrons. An arrangement such as in Fig. 2 where the negative ion must drift large distances at low energies is particularly sensitive to a small pressure as can be seen by comparing it to that observed by the tube of Fig. 5.

Finally, I come to the point that is no doubt bothering many of you. This is the fact that measurements of the coefficients required seem to be low by almost an order of magnitude. This was true for Leland and Olson.⁷ However, their measurements were not made on the surfaces present in a tube that is undergoing loading. When ion exchange loading is present there is a lot of unconditioned surface being covered with freshly sputtered material which is neutral and so may not adhere well. My belief on this point is simple and is that when the coefficients are made with the ions involved and on the types of surfaces present in an accelerating tube that the coefficients will be found to have a summed produce of unity at the threshold voltage for dark current.

There is one problem that our data does not properly cover and that is the possibility of heavy ion clusters being present. One needs a much bigger

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magnet than we used and a somewhat more sensitive detector than we used to properly pursue this point. Leland and Olson did observe that the yield of secondaries increased with the mass of the bombarding atom. Clusters of atoms or clumps as proposed by Cranberg,¹³ are not ruled out by our experiments as being part of the multiplicative process. We recently acquired a large 90° magnet capable of bending product 320 proton MeV particles. Perhaps we should use it with a photomultiplier as a detector.

Cranberg made much of the square root law in his paper.¹³ I have the feeling that this square root law, which as he showed applies empirically to the breakdown voltage over a wide range of conditions, will also be found to apply to the threshold voltage for the ion exchange process when the measurements are complete. We have frequently noticed that the appearance of the dark current enormously increases the probability of sparking. I hope this conference will stimulate measurements that will resolve this problem.

As indicated in the text, this work involved considerable effort by R. K. Beauchamp, Dr. Keith Boyer, and especially James Henshall. Both Boyer and Henshall have been away from this work for over 5 years.

13. See L. Cranberg, "The Initiation of Electrical Breakdown in Vacuum," J. Appl. Phys., 26, 596 (1955).

<u>MASS</u>	<u>+ IONS</u>	<u>PLAUSIBLE POSITIVE IONS</u>	<u>- IONS</u>	<u>PLAUSIBLE NEGATIVE IONS</u>
Electrons			$700 \times 10^{-9} \text{A}$	
1	$4.5 \times 10^{-9} \text{A}$	H	$1.4 \times 10^{-9} \text{A}$	H
2	0.2	H ₂		
3	0.01	H ₃		
7	0.09	Li ⁺		
12	0.15	C	0.03	C
13	0.04	CH	0.01	CH
14	0.03	CH ₂ and N		
16	0.2	O	1.1	O
17	0.04	OH	0.2	OH
23	0.25	Na		
24	0.1	Mg	0.04	C ₂
25			0.03	C ₂ H
26			0.05	C ₂ H ₂
27	8.1	Al	0.05	Al
32			0.04	O ₂
35			0.54	Cl ³⁵
37			0.18	Cl ³⁷
39	0.1	K		
43	0.09	AlO	0.69	AlO
52	0.15	Cr		
54	0.1	Al ₂		
59			0.58	AlO ₂
63	0.02	Cu		
70	0.1	Al ₂ O		
71	0.4	Al ₂ OH		
88 ± 1	0.04	Al ₂ O ₂ H ₂ (88)		
102			0.07	Al ₂ O ₃
117 ± 2	0.06	Al ₂ O ₄ H ₂ (120)		
TOTAL	About $15 \times 10^{-9} \text{A}$		About $5 \times 10^{-9} \text{A}$	

Table 1. These are the results of magnetic analysis of the ions from the tube of Fig. 4. This table is as prepared in 1956. There are probable errors in the assignment of the heavier ions.

Fig. 1. Experimental arrangement used in 1950 to determine the positive ions per electron from 0.7 MV to 1.4 MV. The top plate with the screen collected the returning positive ions. A general bias of 500 volts was applied to prevent electrons from leaving the collector. The filament reached far enough into the potential saddle region so electrons from it could get to the bottom plate of steel. The 3 volt bias was used so the thermal electrons were not collected. The same tube with only a single insulated plate at the top instead of the filament assembly first demonstrated the big effect of biasing the top plate and also the effect of slightly raising the pressure of the vacuum region.

Fig. 2. Experimental arrangement used in 1950 to demonstrate that preventing electrons from returning to the bottom plate did not noticeably change the threshold voltage. The loading threshold was found with the magnet away, then the magnet was brought up causing the electrons to strike the acrylic plate in its vicinity. This caused the electron current to flow through meter B instead of meter A and also stopped the production of x-rays. Supply B worked best at 3 kV and that plus the 300 volt battery gave the optimum focus. The threshold voltage started at 1.1 MV but conditioned up to 1.5 MV.

Fig. 3. Experiment attempted in 1950 on magnetic analysis of the positive ions involved in the dark current process. The bar magnet was brought up to prevent the electrons from making x-rays. The fluorescence did not show up the Fe atoms from the bottom which must have been present but mass 1 and 2 were clearly visible. The crude magnet calibration was checked by proton range in aluminum foil and both gave 1.7 MV as the maximum voltage on the tube. The bottom 3 gaps or 1.5 inches of the tube were shorted on this and previous tests since this gave us more voltage across the tube. Potential distribution was by corona points.

Fig. 4. Experimental setup used in 1956 to get the mass analysis of both positive and negative ions. The results are given in Table 1. The discharge from the bottom passed through the 1" hole in the plate terminating the tube, next passed through a 5/8" hole, and the quadrupole lens. The ions were focused in lines separated by the magnet on central Faraday cup slit at the top.

Fig. 5. This tube was used in 1959 in place of the tube shown in Fig. 4. This basic tube would hold 1.05 MV where it would "silently" spark but not load. All electrodes were aluminum alloy #2024 and were well polished. The very bottom ring outside of the high voltage region was shorted out as indicated on the drawing. HBM resistors of value 2×10^9 ohms were mounted outside of rings but inside of the hoops. It was necessary to introduce the electrode shown dotted on the bottom end of the field region to get steady ion currents. The threshold voltage then was in the range 450 to 625 kV. Mass analysis of the dark current in this tube was as shown in Figs. 6 and 7.

Fig. 6. Mass spectrum of the positive ions from ion exchange leaking in the tube of Fig. 5. The vertical scale is logarithmic except near 0.003×10^{-9} amperes where the converter dropped out, therefore the base line is an artifact of the apparatus. Note that aluminum ions were present by a factor of over ten greater than anything else. The $^{27}\text{Al}^{++}$ peak is explained in the text. The heavy complex ion shown as 113 may well be say Al_5 and contain two atoms of hydrogen.

NEGATIVE CURRENT TO SLIT CUP

Fig. 7. Mass spectrum of negative ions from ion exchange loading in the tube of Fig. 5. Same comment on the base line as in Fig. 6 applies except here we had noise trouble since the vibrating reed amplifier was set 100 times more sensitive. This was a very lucky run and the focus was not so sharp. The peak at 60 was designated 60 rather than 59 partly because of Leland and Olson's results. This does demonstrate that negative ions are something one should be able to eliminate by careful technique.

Fig. 8. Positive secondary ions from a 2024 aluminum alloy target bombarded by 100 keV N_2^+ ions. This graph is reproduced here by the permission of Leland and Olson⁷ who believe their Al^+ peak is off scale by about a factor of 50. Now copper is supposed to be present to about 4% in this alloy yet is only present by 0.8% in this run. The Al_2^+ peak was present by about 1.0-1.2% of the Al^+ intensity in our runs also shows up here with about that intensity.

Fig. 9. Negative secondary ions from a fresh 2024 aluminum target bombarded by 100 keV N_2^+ ions. This target obviously had considerable organic contamination. Reproduced here by permission of Leland and Olson.⁷

Fig. 10. Negative secondary ions from the same target of aluminum as for Fig. 9 except it has been cleaned up by bombardment. Now the contamination is much lower than present in Fig. 7. Reproduced from Leland and Olson's report by their permission.