The Production and Focusing of Intense Positive Ion Beams

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Based on a suggestion by Dr. F. L. Mohler, a high intensity source of positive ions utilizing a gaseous low voltage arc constricted by a metal capillary has been developed. With 250 watts input and 10-cc gas flow per hour, this source delivers controllable positive ion currents up to 1.5 *milliamperes* through a probe canal 1 mm in diameter. The focusing of weak and intense positive ion beams by various electrostatic lens arrangements has been empirically investigated, giving additional data on quantitative design concerning the multiple section high voltage tubes long in use in the laboratory of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and indicating the requirements met in delivering the total ion current from the source onto a target at the far end of such a tube.

(A) INTRODUCTION

We have described[1] the technique developed in the laboratory of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for studies of nuclear transmutation, utilizing electrostatic generators and cascade type high voltage tubes. The focusing characteristics of multiple section high voltage tubes have been rather strikingly demonstrated, and in spite of the limitations of the low voltage arc ion source used in the experiments with a poorly aligned tube provisionally installed it has been possible to concentrate currents of 5 to 10 microamperes of protons or deuterons (after magnetic analysis) on targets less than 1 cm in diameter for hours at a time. However, the ordinary type of ion source used here has given us a certain amount of trouble and inconvenience, and has been proved incapable of delivering more than 10 to 25 microamperes total ion current into the tube (frequently less) even with a comparatively high gas flow (deuterium consumption). Above 1000 kilovolts, currents of one to ten microamperes are ample or even excessive for the study of many transmutation problems, but for the study of relatively infrequent processes, and especially for investigations at lower voltages, higher currents are necessary and a trouble-free ion source capable of delivering hundreds or even thousands of microamperes has been sought in various laboratories as well as here. A low voltage arc, such as used at this Department for nearly three years, can readily supply ion currents of some milliamperes to a probe several cm^2 in area immersed in the plasma and, if the probe is a simple gauze or mesh or is perforated with a large hole, such currents can be projected into an apparatus for further acceleration or use.[2] However, if the current density to the probe is such that a hole 5 to 10 mm in diameter is required to pass the desired ion current, not only are the pumping requirements formidable if a low pressure is to be maintained in the apparatus beyond the probe, but the gas consumption itself becomes so enormous as to prohibit the use of deuterium, and deuterium ions are perhaps the most important of all bombarding particles for transmutation experiments. In the course of numerous tests here a new type of low power ion source has been evolved, delivering large ion currents with very modest gas consumption as described below (section B).

The production of an intense stream of ions is only half the task, however. The problem of concentrating the ions into a beam and then preventing this beam from diverging unduly between the source and the target or other point where the ions are utilized, is of equal importance. Especially at high current densities (many milliamperes per cm^2) space-charge effects influence the beam, as well as the aberrations of the simple electrostatic lenses ordinarily used for this purpose; both factors constitute limitations requiring empirical study. In our experience at this Department with several multiple section high voltage tubes of very dissimilar design we have consistently obtained at the

[1] M. A. Tuve, L. R. Hafstad and O. Dahl, Phys. Rev. **48**, 315 (1935).

[2] E. S. Lamar and O. Luhr, Phys. Rev. **46**, 87 (1934); R. D. Fowler and G. E. Gibson, Phys. Rev. **46**, 1075 (1934).

target, after a crude but obviously necessary adjustment of the available focusing parameters (adjustment of voltages on those tube sections through which the ion beam is traveling slowly), practically the entire ion current which enters the tube from the ion source. Workers in other laboratories, using high voltage tubes having similar cylindrical electrodes but with only one or two sections, have reported a much smaller effectiveness in focusing the ion beam entering the tube, most of which is lost before reaching the target. Bombardment of the walls of the tube by this "lost" portion of the initial ion current is undesirable for several reasons in addition to the simple loss of intensity at the focal spot. Before constructing a more permanent tube to replace the provisional one used, it appeared desirable to examine the relative importance of the numerous factors which determine the focusing of an ion beam by a system of cylindrical electrodes, with particular reference to numerical magnitudes (voltage ratios, dimensions, electrode designs) and to the extent to which space-charge effects and the aberrations of the electrostatic lenses are important in the focusing of large ion currents into small area beams without loss. A tendency toward poorer focusing had apparently been observed with our tubes at currents above 2 microamperes, and this tendency might be exceedingly important at currents of 100 to 1000 microamperes. Although a considerable amount of theoretical and experimental work has been done in recent years on the problems of "electron optics," very little of the material is directly applicable to this ion focusing problem until experimentally tested, especially because of space-charge effects; furthermore, the case of cylindrical electrodes has evidently not been treated in detail. Consequently an empirical study of the most important factors in tube design for proper focusing has been made as described in the latter part of this paper.

(B) The Capillary Arc Ion Source

Knowing of the difficulties experienced here due to ion source limitations, Dr. F. L. Mohler of the National Bureau of Standards kindly described to us last summer some preliminary experiments he had made with the ultimate aim of studying the (H^2+H^2) reactions. In these experiments he had obtained very high current density to a negative probe inserted from one side into a low voltage (hot cathode) hydrogen arc in a quartz tube which was provided with a short constriction or capillary (5-mm diameter) at the location of the probe; high ion density, and hence high probe current density, evidently was obtained because of the high arc current density in the constriction. With the help of Dr. C. M. Van Atta, temporarily a guest investigator in this laboratory, we developed[3] an ion source in the autumn of 1934 on this basis which provides positive ion currents of more than one milliampere, if desired, with modest power requirements and low gas consumption (small diameter probe canal). This source in fact gives such high ion current densities (certainly exceeding 200 milliamperes per cm^2) that a major problem is to overcome the divergence of the beam arising in part from the mutual repulsion effects of space charge, tending to disperse the ions before and as they are accelerated to form a high speed beam. We had previously anticipated and experienced such effects with ion densities of only a few microamperes per mm^2 at low voltages, and it is of importance in various applications to have empirical data on the extent to which space-charge effects and other causes of divergence can be prevented from limiting the formation of ion beams under specified conditions (voltages, distances, size and shape of electrodes). The limitation of a proton current, due to mutual repulsion effects, to a "theoretical maximum" of 10 milliamperes per square centimeter in the ideal case of plane parallel electrodes with a gradient of 10^5 volts/cm, mentioned[4] at the London Conference, thus appears to be greatly modified by the conditions in this source.

In many applications, as well as in our own, it is impossible to utilize an ion source requiring many kilowatts of power—with its attendant necessity of artificial cooling—especially if large and bulky auxiliary apparatus such as a 50-kv rectifier set is essential to its operation. In these

[3] M. A. Tuve, O. Dahl and C. M. Van Atta, Phys. Rev. **46**, 1027 (1934).
[4] M. L. E. Oliphant, Int. Conf. Phys. London, 1934 **1**, 144 (1935).

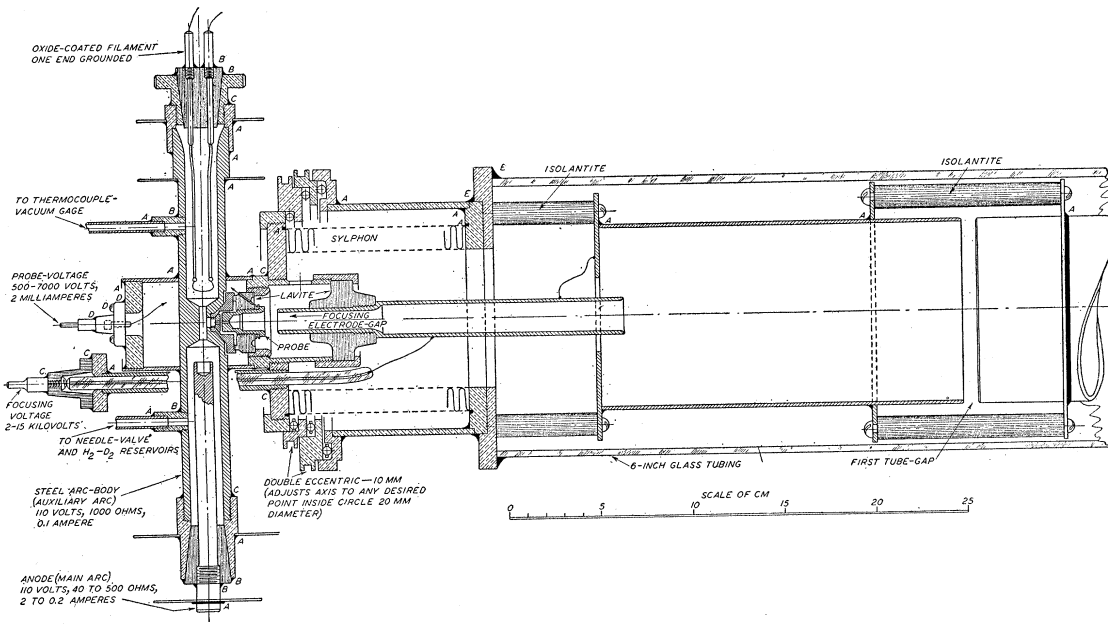

FIG. 1. Ion source with first focusing gap of high voltage tube. A—Tin solder; B—rock cement and glyptal or De Khotinsky cement; C—picein; D—De Khotinsky cement; E—Apiezon plasticene "Q".

respects and in its simplicity of control, the capillary arc ion source has fortunately proved advantageous.

(1) Construction

The complete ion source as attached to the high voltage tube is shown in Figs. 1 and 2 in which the important features of the arc, probe and focusing electrodes are shown to scale. Referring to Fig. 2, the arc is confined by a steel capillary, bored out of the solid steel cylinder A, the arc capillary B (3.5-mm diameter, 18 mm long) joining the arc spaces containing the oxide-coated filament C and the steel anode D. A side volume E (diameter 5 mm) was bored out as shown for the diffusion of ions from the capillary arc to the probe, and the conical steel insert J serves to provide flat gas seal surfaces between the arc space and the evacuated high voltage tube. The steel probe F is mounted on the lavite[5] insulator K and is provided with a canal H, 1 mm in diameter by 4 mm long, through which the ion current (as well as gas flow) passes into the evacuated high voltage tube. The steel "button" G is inserted to act as a partial diaphragm at the lower end of the space E. Introduction of this button diaphragm reduced the total current to the face of the probe F (including secondaries) by a factor of

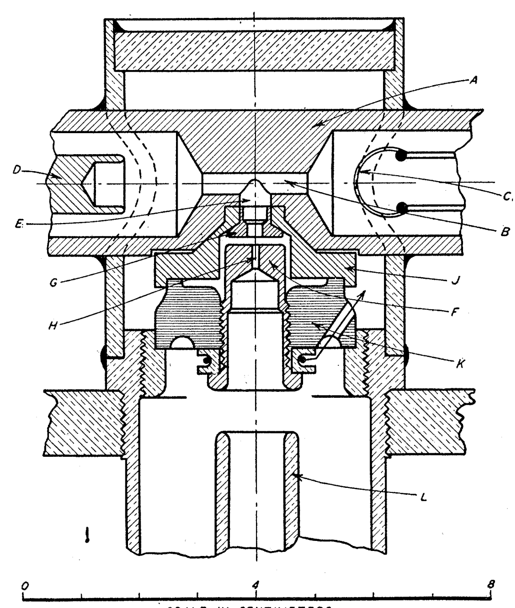

FIG. 2. Ion source detail.

[5] Finest grade unfired imported steatite, purchased from American Lava Corporation, 1420 Williams Street, Chattanooga, Tennessee. Insulators of any shape are readily fabricated from this material; they expand slightly on firing at about 1000°C for one hour.

4 or 5, and, evidently by causing a more favorable curvature of the space-charge sheath separating the negative probe from the arc plasma, it also served to concentrate the probe current on the canal H, increasing the current through the probe canal by a factor between 2 and 3 at various voltages. The ion stream projected through the probe canal H rapidly diverges (the initial ion paths, due to the space-charge sheath, are not parallel), and an initial "focusing gap" very near to the probe canal is incorporated as a part of the ion source, to deliver to the first section of the high voltage tube, in the form of an ion beam of the proper characteristics (speed, divergence, beam area) to suit the focusing-parameters of that tube section and those which follow, the total ion current which emerges from the probe canal. This initial "focusing gap" is formed by the cylindrical end of the probe and the cylindrical electrode L, which is held at a controlled direct-current potential of 2 to 15 kv —the correct voltage depending on the probe voltage and the focusing properties (voltage is the chief variable) of the first tube sections. The probe voltage (100 to 4000 volts, see Table I) is supplied, through the connection indicated by arrows in Figs. 1 and 2, by a filtered rectifier using type '66 tubes, and the focus voltage (2 to 15 kv serves for all but the extremely high currents, see below) is supplied by a half-wave unit using a ZP-85 kenotron. Protective resistors (50,000 ohms) are essential in the probe and focus voltage leads to prevent "blowing out" the arc (possibly by oscillations). The ease of accurate control of the tube current (probe voltage) and spot focus (focus voltage) by autotransformers of the Variac[6] type is important enough to mention. The complete ion source is mounted on a large sylphon and provided with a double eccentric arrangement to make it possible to move the point-source of ions with respect to the lens system, thus providing an optical lever arrangement for moving the focal spot.

(2) Operating characteristics

The total power consumption of an ion source is an important factor in many applications; in the range of currents covered by our tests the power required for this source is of the order of 250 watts or less. The cooling-fins shown in Fig. 1 keep the temperature low enough for the wax seals without it, but we usually direct the breeze of a "toy" electric fan on the source when in use. The arc readily operates on 110 volts direct current, with an external resistor controlling the arc current (0.2 to 2.0 amperes—usually 1.0); the voltage drop across the arc itself is about 55 volts, the "floating" arc body assuming a potential 22 to 30 volts above the filament, which is grounded. The filament power is appreciable, a 4-mm by 14-mm strip of 2-mil platinum drawing 16 amperes at 3 to 6 volts. The oxide coating[7] of the filament requires occasional replacement, but lasts for more than a month of daily use with hydrogen. The power requirements for the probe and focus voltages are almost negligible (except for the losses in the rectifier units). The arc through the capillary can be struck by the application of a "leak tester" (spark coil) to the floating arc body; it will continue to run at a pressure somewhat lower than that required for striking. A self-striking auxiliary arc (0.2 ampere) to the steel arc body surrounding the filament will operate at a slightly lower pressure than will the main capillary arc, and it serves to restrike the latter arc, if it goes out for some cause (too low pressure, too high probe voltage), as soon as the cause is removed, except when extreme purity of the hydrogen makes the arc difficult to strike. This may be of importance in certain applications requiring intermittent bursts of ions. The auxiliary arc reduces the ion current output of the source at the higher probe voltage values, however, and should be omitted if maximum ion currents are desired.

The actual pressure of the hydrogen in the arc and the rate of flow of gas through the probe canal have not been ascertained with precision. Crude records of the number of hours a 1-liter flask of gas will operate the source indicate a flow of about 10 cc per hour (normal pressure and temperature), allowing the use of deuterium without recovery at nominal cost. An Apiezon

[6] Supplied in three sizes by General Radio Company, Cambridge A, Massachusetts.

[7] The regular oxide mixture of the radio tube trade, purchased in liquid suspension from Callite Products Company, Union City, New Jersey, is used.

pumping-system with a speed (for air) of about 30 liters per second maintains a pressure of about 2×10^{-5} mm in the high voltage tube (Western Electric ionization gauge, type No. D-79510, reads 6 to 10 microamperes at 20-ma emission) when the pressure in the arc is perhaps 2×10^{-3} (General Electric thermocouple vacuum gauge, catalog No. 3850264-Gl, with 50-ma heater-current, reads 90 to 60 microamperes at arc pressure and 200 microamperes for zero pressure). The arc appears to operate at lower pressures if the hydrogen in the arc space is not 100 percent pure; this is usually insured by the gas evolution of the oxide-coated filament, but we have also introduced small amounts of air or helium into the hydrogen reservoir with apparently a similar result, although our experience with the older form of low voltage ion source used here for several years definitely shows that the introduction of small amounts of air with the hydrogen reduces the numbers of hydrogen-ions (of various kinds) by as much as a factor of 10.

(3) Output ion currents

The ion current output from the 1-mm by 4-mm probe canal shown in Fig. 2 has been measured, as a function of probe voltage, arc current, pressure and other variables, by utilizing the cylindrical electrode L and all subsequent electrodes (larger diameter) as a very deep Faraday cage. Some effect of secondary electrons is obvious, but making the Faraday cage successively 45 volts plus and minus with respect to the probe shows that the usual equal potential measurement indicates approximately the true ion current, as indicated below. [Note: The focus gap FL was shortened to 3.5 mm during most of these measurements, later left at about 7 mm; these changes were of practically no effect on the focusing-characteristics of the gap.] A typical series of measurements of the total ion current output from the probe canal is given in Table I. Many of the current values were duplicated within about 10 percent after focusing (by application of the proper potential to electrode L) into a similar Faraday cage beyond L and at its potential, a further indication of the absence of very large secondary emission errors in the current measurements.

TABLE I. *Total ion current output of probe canal as a function of probe voltage and arc current.* (Arc pressure, 100μA on thermo-gauge; hydrogen plus 10 percent air; auxiliary arc, 0.13 ampere.)

Arc current (amp.)	Probe voltage 700 (μA)	1000 (μA)	1500 (μA)	2000 (μA)	4000 (μA)	7000 (μA)
0.25	**50**	75	82	70	52	40
0.5	40	**94**	**161**	200	150	110
1.0	19	50	157	**290**	450	410
1.5	14	30	90	260	**770**	990
2.0	12	22	58	170	750	1410
2.5	..	..	...	...	710	**1600**

We have evidence indicating a secondary electron emission of from 100 percent to 500 percent of the ion current itself when a flat metal electrode is used to measure the current instead of a deep Faraday cage, a source of serious errors not always fully appreciated in work of this kind.

The ratio of atomic to molecular ions is undoubtedly dependent on the hydrogen pressure, impurities and other operating factors, but in our experience with a great variety of low voltage arc arrangements used as ion sources we never have observed fewer than 50 percent, and never more than 90 percent atomic ions, the balance of the hydrogen ions being often largely triatomic. This source shows the same behavior.* [We have had occasion so far to make relatively few measurements of ion ratios with the capillary type source and these have not been made at the very highest currents, but there is no reason to suppose that the number of atomic ions should decrease with higher probe voltages.] The exact ratio of atomic to molecular ions

* *Note added in proof:* We have recently had opportunity to make more extended measurements on the ion varieties emitted by the capillary-arc source. With the probe-canal shown in Fig. 1 and using tank-hydrogen, only 20 to 30 percent of the hydrogen ions are atomic; as with our other sources, the hydrogen ions constitute one-half to three-fourths of the total. With 2000 volts on the probe and 70 kilovolts on a single-section tube, typical currents in the separate spots after magnetic analysis are: Mass 1, 22 microamperes; mass 2, 32 microamperes; mass 3, 36 microamperes; mass 4, less than 0.1 microampere; masses 16, 17 and 18, 36 microamperes; total (measured before entering the long analysis-chamber), 162 microamperes; sum of all measurable spots, 126 microamperes. The distances in this arrangement were known to be too great to prevent the loss of part of the ion current at this low tube-voltage before it reached the target, placed in a deep Faraday cage beyond the magnet. Ordinary tank-hydrogen gives a better proton-ratio than hydrogen diffused through palladium, or hydrogen mixed with air, helium or water vapor. By collision-dissociation of the molecular ions after attaining appreciable speeds, a longer probe-canal gives a better proton-ratio, although the total currents for a given probe-voltage are much reduced. Modifications should be possible to enhance this dissociation effect.

TABLE II. *Variability of output current—effects of secondary electrons.*

Probe voltage (volts)	Cage voltage (volts)	Arc = 1 ampere Thermo-gauge pressure 60μA No aux. arc (μA)	Arc = 1 ampere Thermo-gauge pressure 90μA No aux. arc (μA)	Arc = 1 ampere Thermo-gauge pressure 90μA Aux. arc, (0.3 amp.) (μA)	Arc = 2 amperes Thermo-gauge pressure, 90μA No aux. arc (μA)	Arc = 2 amperes Thermo-gauge pressure, 90μA Aux. arc, (0.3 amp.) (μA)
100	100	1.5	...	...	....	...
200	200	2.3	...	...	....	...
500	500	7.2	...	...	....	...
1000	1000	28	32	...	22	...
2000	2000	230	250	250	155	230
4000	4000	600	570	280	800	740
6000	6000	680	590	210	1110	810
6000	6045	...	460	...	940	...
6000	5955	...	850	...	1500	...

coming from the source is of no importance in our experiments since magnetic analysis is used at the target, as it always should be if the variety of ion is of importance. If capture and loss phenomena take place after acceleration and before magnetic analysis, there will of course be an overlapping of ion varieties. Such capture processes occur only to a negligible extent in our high voltage tubes, as indicated by the lack of any ions at the target more readily deflected than the full speed protons.

It is to be noted that an optimum value of arc current (for maximum output current) exists for each probe voltage, increasing with the latter, as indicated by the current values in bold face type. These current values do not duplicate exactly on different occasions with slightly changed conditions, but the extent of the variation, as well as the effects of secondary electrons, may be seen by comparison with Table II.

The output currents do not appear to vary greatly with pressure over the working range of pressures used. The pressure is usually set at a value not much higher than is necessary to prevent extinction of the arc. Much larger output currents undoubtedly can be obtained, if desired, by increasing the size of the probe canal at the expense of increased gas consumption, or as indicated by Table I by increasing the arc current through the capillary and raising the probe voltage to its corresponding optimum value.

(4) Dependence on configuration and other variables

The effect of the auxiliary arc on the output current from the probe canal has been mentioned above, as well as the changes brought about by

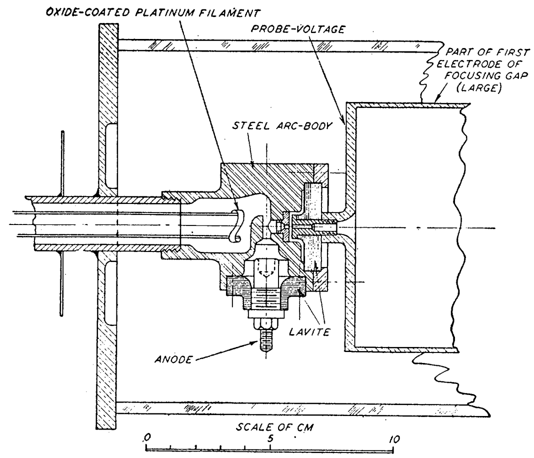

FIG. 3. Right-angle capillary—ion source.

the diaphragm button *G* ahead of the probe. Before the introduction of the latter, the position of the probe face was varied in steps from 1 mm inside the arc capillary itself to its final position as shown in Fig. 2. Except for the fact that the arc was extinguished by probe voltages as low as 500 to 1000 volts, no great dependence on probe position was observed. The current to the probe face (4-mm diameter) was roughly constant at about 8 milliamperes for all probe voltages from 20 volts to extinction. The diaphragm button *G* allowed much higher probe voltages to be applied without extinguishing the arc. The few brief tests which have been made with probe canals of diameters differing from the standard 1-mm diameter indicate that the output current increases somewhat more than in proportion to the area of the probe canal. It must be remembered that the gas flow increases with the cube of the diameter of this canal, however. The gas flow is inversely proportional to the length of the canal, but the dependence of the ion current on the canal length is a function of the probe voltage in question, probably on account of changes in curvature of the space-charge sheath, giving different degrees of divergence to the initial ion stream. For medium values of probe voltage it varies more rapidly than the inverse square of the length of the canal. This is a crude statement but may be of assistance in adapting this design to other conditions. For low probe voltages the "best" probe canal is a diaphragm in a thin plate; for higher voltages the canal profitably can have appreciable length, thereby decreasing the gas flow without seriously decreasing the output current by loss to the sides of the canal.

For reasons of convenience (removal of filament) in a particular application we constructed a modified form of the capillary arc source, differing from that of Fig. 1 by the fact that the arc was struck "around a corner" as shown in Fig. 3. It was astonishing to discover that this source had characteristics rather widely different from those of the original design. Because of a slip, the side volume E at first was bored out slightly off-center with respect to the arc capillary, which was 3.5 mm by 18 mm as before. When the arc required 75 volts and showed an anode drop (with respect to the capillary) equal to the former total arc voltage (50 volts) with the total probe current only 200 microamperes, it was thought that no arc was passing through the capillary. The latter was consequently shortened to 9 mm with but slight effect. The arc capillary was then bored out to 6.5 mm diameter and centered with respect to the probe axis. With an arc current of 1 ampere (low density because large capillary) a probe canal 1 mm by 4 mm as before gave an output current of only 38 microamperes at 2000 volts instead of about 230 microamperes with the source of Fig. 1. The output current was found to show rather sharp maxima with increasing probe voltage and arc current, and even the optimum values were only about one-eighth of the normal output of the original source at a given voltage. The arc capillary was then plugged and rebored to a diameter of 3.5 mm and length of 10 mm, centered on the probe axis. The probe canal output current was raised by this to about one-third of the value for the straight capillary but it still showed a strong dependence on arc current and sharp maxima with the latter and with probe voltage, as indicated in Table III.

TABLE III. *Right-angle capillary arc: Dependence of probe canal output current on arc current and on probe voltage.*

Probe canal, 1 by 4 mm; Thermo-gauge pressure, 75μA			Probe canal, 0.51 by 9.5 mm; Thermo-gauge pressure, 70μA		
Probe voltage (volts)	Arc current (amp.)	Output current (μA)	Arc current (amp.)	Probe voltage (volts)	Output current (μA)
2000	0.25	6	0.9	4000	11
	0.5	16	1.2	2000	5
	1.0	68		3000	16
	1.25	62		4000	21
	1.50	46		5000	12
	3.0	28	2.2	2000	4
	5.0	22		3000	9
				4000	28
				5000	50

Thus, although the behavior of the ion source of Fig. 1 has been consistent throughout months of use and a great variety of changes (exceeding 30) of various associated parts, the behavior of the right-angle arc of Fig. 3 remains an interesting but unimportant mystery. It is described solely to indicate the extent of our recommendations for changes in the source shown in Fig. 1 on the basis of the few variations we have tried.

(5) Tests of various electrostatic lens arrangements: The focus gap *FL* of the ion source

On the assumption that it might be important, because of space charge and initial divergence of

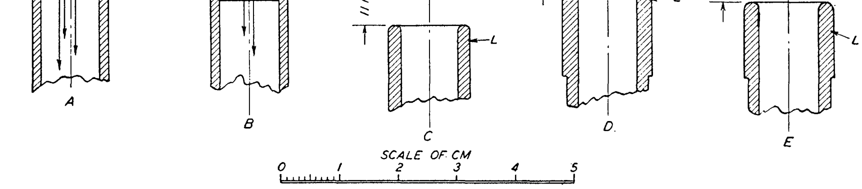

FIG. 4. Electrostatic lenses adjacent to probe canal.

TABLE IV. *Variation of current into Faraday cage with 2000 volts in probe F and canal output 230 microamperes (case a of Fig. 4).*

Focus voltage on *FL* (volts)	Current into Faraday cage (μA)
4000	6
6000	10.5
7000	13.5
8000	3.2
10000	0.5

the ion paths, to place a focusing lens as near as possible to the output end of the probe canal early tests were made of the arrangements shown in Figs. 4*a* and 4*b*. As a test of the focusing, the currents were measured which passed into a long Faraday cage (50 cm long by 6 mm diameter) through a 5-mm hole in a diaphragm at the lower end of electrode *L*. For the first case (4*a*) this 5-mm hole was 20 cm below the arc capillary (18 cm below the lens *FL*), and it was found that a peculiar "over-focusing effect" occurred; only 5 percent of the total current could be passed as a beam through the hole. This was erroneously thought to be a space-charge effect leading to an "excluded" zone at a distance as large as 20 cm, the ion paths switching sharply from "under-focused" to "over-focused" (crossing axis) at a value far below that (virtually) necessary for focusing. The 5-mm diaphragm was consequently moved nearer to the lens, to a position 14 cm below the capillary, and the larger lens 4*b* was tested. This was much better, although still delivering only about 35 percent of the ions into the cage, as shown in Table V.

It is probable that both lenses per Fig. 4*a* and Fig. 4*b* failed to form good ion beams because their dimensions were comparable to the dimensions of the incident divergent ion stream. The probe canal, as in all subsequent measurements, was 1 mm in diameter by 4 mm long, thus permitting initial ion paths throughout a cone of rather large angle from an initial area 1 mm in diameter. The aberrations of a simple lens for a beam as large as one-third its own diameter are probably large, but it is also desirable (unless initial side components of velocity are negligible) for the lens to be far enough removed, from a source of finite area which emits ions in a variety of initial directions, to permit the ion paths to separate, so that those ion paths entering a given (circular) zone of the lens all make the same angle with the axis. When this condition is fulfilled, the requirements on the lens are obviously much less stringent.

Adopting lens electrodes of still larger diameter, further removed from the ion emitting area (end of the probe canal), the arrangements *c*, *d* and *e* of Fig. 4 were tested. With the 5-mm diaphragm (into the Faraday cage) at the original distance of 20 cm, the lens 4*c* gave a fairly satisfactory beam, 11 kilovolts serving to focus through the 5-mm hole the total output of the probe canal at 2000 volts (230 microamperes). A wider gap (14 mm) required the application of a slightly higher voltage (15 percent) before complete focusing was attained (at any given probe voltage) and with the narrow gap 4*d* (3 mm) a slightly (20 percent) lower voltage sufficed, but otherwise little variation with electrode spacing could be observed. The medium gap of 4*c* (7 mm) was chosen for further tests (this lens was adopted in the final arrangement as now used).

It was observed that as the output current of the probe canal was increased by increasing the probe voltage, the voltage required on the lens *FL* to focus the ions in a beam through the 5-mm diaphragm was also higher. To determine whether this was in part due to increased mutual repulsion and consequent space-charge dispersion at the higher beam currents or simply to the increased "stiffness" of the beam (higher initial velocity of ions as they enter the lens) with increasing probe voltages, measurements were made of the focus voltages required to concentrate the total output current from the probe canal through the 5-mm hole at 14 cm into the

TABLE V. *Variation of current into Faraday cage (case b of Fig. 4).*

Probe voltage (volts)	Canal output (μA)	Cage current (μA)	Required focus voltage (kv)
2000	230	105	14 (max. available)
1500	93	34	10–14
1000	28	10	5

TABLE VI. *Observations showing focus voltage proportion to voltage (energy) of incident ion beam.*

Probe voltage (volts)	Output currents (μA)	Required focus voltage (kv)	Faraday cage current (μA)
100	1.5	1.0	1.4
200	2.3	1.5	2.3
350	4.5	2.5	4.3
700	12	6.0	13.3
1000	28	8.0	33
1200	....	10	55

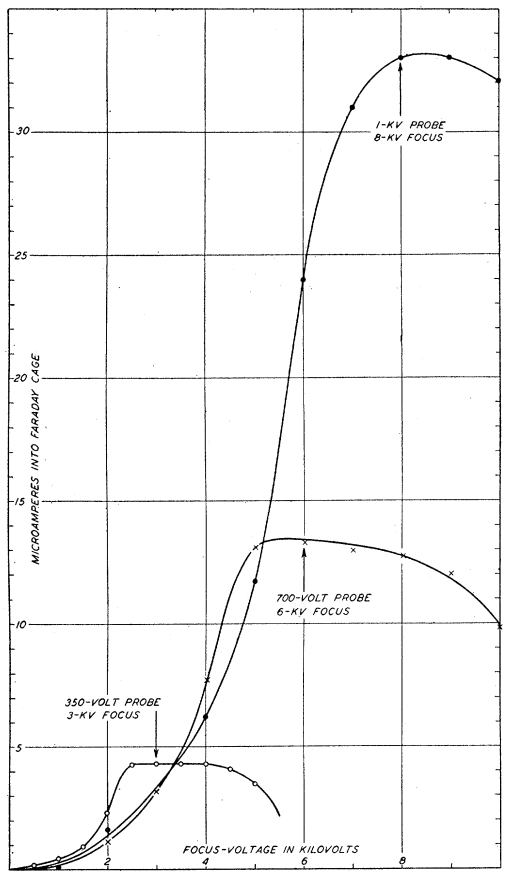

FIG. 5. Typical curves showing importance of initial ion beam "stiffness."

Faraday cage. Typical curves are shown in Fig. 5, and the results are summarized in Table VI.

The approximate proportionality of the probe voltages and required focus voltages indicates the lack of space-charge effects and the importance of the "stiffness" of the ion beam.

Tests of the distances which the ion beam could be made to travel without undue dispersion were next inaugurated. The Faraday cage tests using the 5-mm diaphragm hole as well as corroborative tests with a fluorescent screen, showed that the lens 4*c*, at a distance from the probe canal as shown, was able to concentrate all of the ions from the probe canal (at least up to 350 microamperes) into a beam which would travel a distance of 20 cm without much dispersion, most of the ions striking an area about 2 mm in diameter when the focus voltage was correctly adjusted. A large (8-cm) fluorescent

TABLE VII. *Observations on focusing with single lens and 85-cm target distance (case e of Fig. 4).*

Probe voltage (volts)	Output current (μA)	Required focus voltage (kv)	Faraday cage current (μA)	Diameter focal spot (mm)
350	4.5	2.8	5	8
500	7.2	3.9	9	7
700	12	5.4	15	Diffuse > 10
1000, > 1000	No focal spot—annular rings and background			

screen was installed at a distance of 85 cm from the arc capillary in a crude Faraday cage of wire mesh. When projected this distance through an equipotential cylinder extending to the cage and screen, the lens 4*e* gave a definite but rather large focal "spot" for currents under 10 microamperes, but the beam spread over the whole screen with larger currents (higher voltages) as shown by Table VII.

That this failure to give a good focal spot at higher currents would not be overcome to any large extent if the lens 4*e* had considerably less "curvature" and hence projected a higher speed beam toward the screen (coming to a focus at the same distance) was unintentionally determined by the introduction of a "negative lens" a short distance beyond the lens 4*e*. This came about in one experiment by neglecting to shield the beam at all points inside a cylinder at the focus voltage, a gap in this shielding permitting lines of force from the surrounding parts at zero potential to enter the cylinders and affect the beam as shown in Fig. 6. This lens combination required a much higher focus voltage (for a given probe voltage) but the spot became diffuse at similar currents under 10 microamperes.

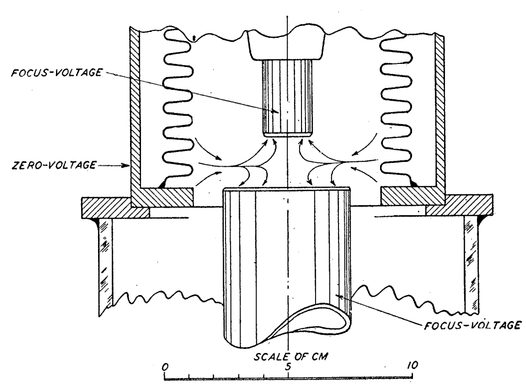

FIG. 6. Accidental negative lens.

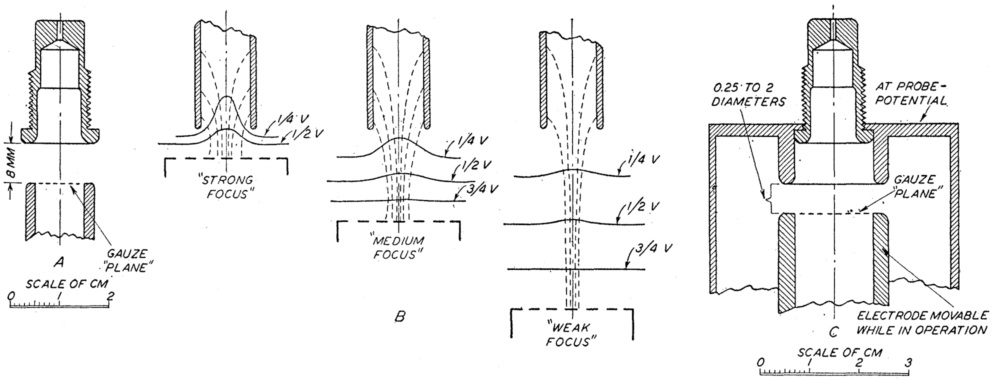

FIG. 7. Cylinder and plane—lens configurations.

The conclusion was reached that either the aberrations of a simple lens having the dimensions (and position) of 4*e* were too great to permit concentrating an ion beam to a distance of 85 cm without large dispersion, or else that this limitation was due to an insufficiently large ratio of the focus voltage to the probe voltage, permitting the side components introduced by curvature of the space-charge sheath in front of the probe to be too important.

Before turning to multiple acceleration through a succession of lenses as a means for carrying a concentrated ion beam to considerable distances, a series of brief tests was made with lens electrodes of other types. The focusing effect of a cylinder and plane arrangement was tested as shown in Fig. 7*a*. This gave a greatly magnified and somewhat distorted image on the screen (×30 at probe 1500 volts, focus 10 kv, screen at 85 cm) of an annular 100-mesh ring used for the plane, the center of the screen remaining dark and the pattern moving outward and enlarging as the focus voltage was increased (or the probe voltage decreased). Blanking off half the mesh by a sheet of metal foil showed that the effect was due to a very strong "over-focusing," the ions passing through the lens on one side of the beam crossing the axis on their way to the screen, and only a narrow (0.1-mm) annular ring or zone in the lens having the proper "focal length" for the screen at a given voltage. It was thought possible that control of the curvature of the lens zones might be effected by varying the gap between cylinder and plane as indicated by the equipotentials sketched in Fig. 7*b*. Installation of an electrode movable by rack and pinion as indicated in Fig. 7*c* showed that this was not the case, no focal spot whatever being obtainable with this arrangement on a screen at a distance of 140 cm, whereas the lens of Fig. 4*e* gave a spot 2 to 3 cm in diameter for currents up to 10 microamperes, even at this long distance.

TABLE VIII. *Observations on focusing with single lens and incidental negative lens (case of Fig. 6).*

PROBE VOLTAGE (VOLTS)	OUTPUT CURRENT (μA)	REQUIRED FOCUS VOLTAGE (KV)	FARADAY CAGE CURRENT[a] (μA)	DIAMETER FOCAL SPOT (MM)
100	1.5	2.5	1.6	<10
200	2.3	4.5	3.7	10
350	4.5	7	(7.8)	Some background
500	7.2	...	(14)	Mostly background
700	12	13	(28)	No spot

[a] Secondaries bad.

With the movable-electrode apparatus several other electrode arrangements were tested. Two modifications of the "negative lens" were tested, as shown in Figs. 8*a* and 8*b*; neither gave a satisfactory spot, although the much higher focus voltages required (22-kv focus for 1000-volt probe gave an annular spot 20 mm in diameter) permitted somewhat better definition at the expense of impracticable voltage requirements. The arrangement of two equal cylinders with variable spacing, shown in Fig. 8*c*, was similar to the standard lens in Fig. 4*e* and behaved similarly, giving a spot 20 to 30 mm in diameter without much background at currents under 10 microamperes but showing bad aberrations at higher currents (probe voltages). A spacing of 18 mm required 50 percent greater voltage for focusing than one of 14 mm, although the variation was less marked as the gap was decreased below this

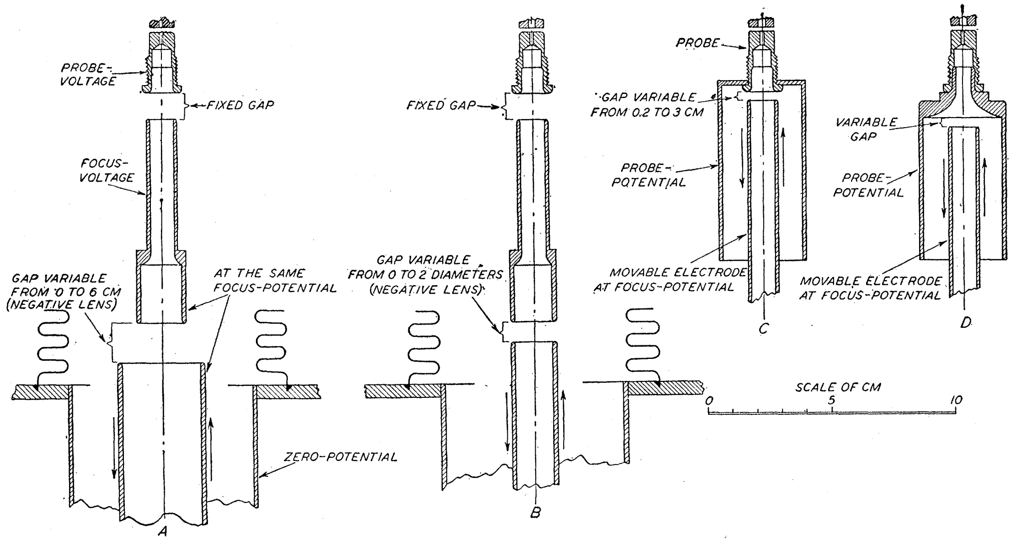

FIG. 8. Negative and positive lenses with electrodes of variable spacing.

to 1-mm spacing, the voltage required for focusing with the latter gap being only about 25 percent less than for the 14-mm gap. The arrangement of a cone and a movable electrode, shown in Fig. 8*d*, was similar in behavior to the cylinders of Fig. 7*c* when the cone-cylinder spacing exceeded 15 mm (the spot was very poor for smaller gaps), and required a somewhat lower voltage for the same focusing effect.

Thus no simple arrangement of electrodes was found which might serve with applied voltages under 25 kv to project a well-concentrated ion beam to distances much greater than 20 cm, especially with beam currents exceeding a few microamperes. Consequently the lens of Fig. 4*e* was adopted for the ion source focus control and tests of the important factors governing the behavior of multiple lens arrangements were begun.

(C) The Electrostatic Focusing of Positive Ion Beams in High Voltage Tubes

In a brief investigation undertaken for the practical purpose of obtaining numerical information on the major factors involved in cascade type high voltage tube design, and which has proved a rational basis for a previously utilized empirical solution of the problem, which is not necessarily a unique solution, no attempt was made at completeness in the academic sense. In view of the scarcity (or absence) of information and data on this problem in the literature, however, it is thought that data on some of the rather poor electrode arrangements tested here may be of nearly as much interest as the simple specification of an electrode system which functions satisfactorily in a high voltage tube. Many discussions, largely innocent of experimental information, have been held regarding the desirability of one electrode arrangement or another for focusing of ion beams; these experiments outline certain features which are important and indicate the relative unimportance of others.

(1) Focusing parameters

Among the variables more or less subject to choice or specification in the problem of ion beam focusing, the following may be listed for discussion and empirical examination.

(*a*) The e/m of the ions should be of no influence in the case of simple electrostatic focusing. If the ions have fallen through the same total potential-difference before entering the "lens," electrons and heavy (negative) ions should describe the same paths, provided space charge can be neglected. This is a serious proviso however. With relatively slow moving ions and until data were obtained on high current densities at specified (low) voltages, no predictions could be made with confidence. It appears from our experiments that space-charge effects in the ion beam itself as it travels are of less importance than the aberrations of the electrostatic lenses, which of course may be in part due to space-charge effects. If the latter is true, however, our experiments indicate that the lens aberrations are of practical importance even with the smaller ion currents. For distances of the order of 100 cm and beam currents above 10 microamperes, mutual repulsion (space-charge) effects in the beam itself probably become important.

(*b*) For the initial speed (voltage) of the ions entering the focusing field (electrostatic lens), the expected linear relationship between the initial voltage of the ions and the voltage required across a given lens to produce a given convergence of the beam is experimentally verified. The importance of lenses introduced where the beam is traveling slowly, and conversely the difficulty of altering the divergence of a high speed beam, are obviously indicated, as is also the clear-cut necessity for controlling the initial speed or the applied voltage, or both, if a beam is to be rendered parallel or brought to a focus at a given distant point by a given lens.

(*c*) The initial divergence of the ion stream affects its path through the lens and beyond and, unless the compensation by the lens is correctly adjusted for all angles of incident cones, we encounter the analog of spherical aberration. In this study we deal with ions of uniform energy emerging from a point, to be focused to a distant point; the analogs of chromatic aberration and off-axis astigmatism consequently are of no concern.

(*d*) The total beam current becomes important if thereby the space charge becomes sufficiently high, as indicated above, altering the field of the lens system and spreading the beam along its path due to mutual repulsion of the ions. Space-charge effects from our experiments appear somewhat less important than other disturbing factors.

(*e*) The beam area must not be too large, if serious aberrations are to be avoided, in comparison with (*f*).

(*f*) The dimensions of the lens (sizes of the electrodes) are important.

(*g*) The distance from the ion source to the lens, implicitly involved in several items above, is important enough to mention explicitly.

(*h*) The distance from the lens to the target or to the next lens is also important.

(*i*) The additive effects of multiple focusing gaps or lenses allow only a limited optical analogy, because of the change in speed or "stiffness" of the beam as it is accelerated by the successive lenses. In general, however, the division of the total voltage among a series of lenses placed at intervals along the total path of the beam probably results in much less aberration or spreading than is evidenced with a single lens using the same voltage and same path length. Our chief information on the behavior of multiple lens arrangements has come from our experience with cascade tubes, described in the paper on our high voltage technique.[1]

(*j*) The quantitative characteristics of various types and sizes of electrodes used for the lenses are of importance in problems of design. The actual voltages required with given electrodes to accomplish a desired focusing of a given ion current are of interest, as well as data concerning the importance of shape and dimensions of various possible electrode arrangements. We have examined to some extent each of the following electrode types:

(1) Equal cylinders—small, medium, large diameter; variable spacing (gap).

(2) Unequal cylinders—beam progressing from small diameter cylinder into large diameter cylinder and *vice versa*.

(3) Cone and cylinder, with variable spacing.

(4) Cone and plane (gauze), with variable spacing.

(5) Cylinder and plane (gauze), with variable spacing.

Our results may be summarized by the statement that if the ion source of Fig. 1 is attached as shown to the first lens (electrode gap) of a cascade type high voltage tube having additional sections exactly the same as the first, spaced not more than 40 or 50 cm apart and carrying 100 to 125 kv each at full voltage, with a beam travel beyond the final lens not exceeding 1 meter per 100 total kilovolts, then with proper adjustment of voltages on the lenses practically all of the ion current output of the source will be concentrated by the tube in an excellent focal spot not more than 2 or 3 mm in diameter.*

* *Note added in proof:* The short Isolantite insulators shown in Fig. 1 were used for spacing the tube-gap in these focusing tests only and will fail if the proportions shown are duplicated in a multiple-section tube for high

Currents as high as 1.0 milliampere from the capillary arc ion source have been concentrated on a 3-mm focal spot with a two-section tube having an applied voltage of 110 kv. Multiple-section tubes have been used at higher voltages but only for small currents.

(2) Characteristics of individual lenses

Although our use of such tubes in transmutation experiments for more than two years had amply demonstrated that simple cascade type tubes having 4-inch diameter cylindrical electrodes separated by gaps of 2 inches, each section being $10\frac{1}{2}$ inches in total length, gave excellent focusing, and the recently developed capillary arc ion source with its focusing lens provided a highly satisfactory means for introducing an ion stream under control into such a tube, it appeared desirable to have further information for purposes of design. For example, information is needed concerning the properties of large and small diameter electrodes, of re-entrant electrodes (possibly desirable from the standpoint of shielding), on the effect of electrode spacing, and on the importance of target distance at low voltages and at high beam currents.

(*a*) *Large diameter equal cylinders, narrow spacing*. Tests were first made of the arrangement shown in Fig. 9*a* with the first "tube lens" at 40 cm from the arc capillary and a fluorescent screen (in a very crude Faraday cage) at a distance of 1 meter (from the arc). This lens was formed by two 4-inch cylinders separated 3/8 inch. It was immediately found that this arrangement gave an excellent (2- or 3-mm) focal spot on the screen provided the voltage on the tube lens was sufficient to prevent dispersion of the ion beam. With a good focal spot the whole of the ion current from the probe canal was concentrated on the screen. The probe voltage was found to have little or no effect on the focusing, the latter being controlled, with a fixed voltage across the tube lens, by the voltage across the lens *FL* of the ion source. The probe voltage consequently served to vary the beam current without appreciably changing the focusing. Tests were carried only to 2000 volts on the probe as another rectifier unit was not available. The data of Table IX show the behavior of this combination.

With the screen at the same distance (1 meter from arc capillary) an identical lens (4-inch diameter, 3/8-inch gap) was tried at a distance of 60 cm from the source as shown in Fig. 9*b*. This lens required the same focus voltages as the source lens *FL* and gave similar red hot focal spots (probably due to incandescent carbon from the material used for mounting the fluorescent salts) but the accompanying "background" was distinctly worse. In further tests the original lens at 40 cm was used with the fluorescent screen removed to a distance of 3 meters in the tube. With no voltage on the tube lens a spot 20 to 30 mm in diameter was obtained with 500 volts on the probe (7 microamperes) and 4.5 kv on the source lens *FL*; but upon raising the probe voltage to 1000 volts the "background" covered the whole screen and the "spot" decreased to the same intensity level. Application of 33 kv to the tube lens with a probe voltage of 1500 and 7.6 kilovolts on *FL*

TABLE IX. *Observations on focusing with ion source lens and one tube lens (case a cf Fig. 9).* [Tube lens, 4-inch electrodes, 3/8-inch spacing; tube pressure 12μA (ionization-gauge).]

Tube lens voltage (kv)	Probe voltage (volts)	Output current from probe (μA)	Required focus voltage (kv)	Faraday cage current (μA)	Diameter of focal spot and ring (mm)
17 less focus voltage $\cong$14 on lens	300	4	2.4	5	3
	500	7	2.6	7.5	3; ring 6
	700	12	2.8	10	Strong ring, 10
	1000	28	2.9	22	Strong ring, 10
	1500	93	3.0	34	Annular ring, 15
	2000	230	3.1	52	Annular ring, 20
33 less focus voltage $\cong$29 on lens	500	7	4.0	..	..
	700	12	5.0	16	1, red hot spot
	1000	28	5.2	38	1, red hot spot
	1500	93	4.8	116	1, very red spot
	2000	230	4.8	163	1, very red spot; ring, 30
50 less focus voltage $\frown$43 on lens	500	..	3.8(?)	8	Poor spot; background (?)
	700	..	5.0(?)	..	(?)
	1000	..	5.0	..	20
	1000	28	7.2	(24 to 30)	2, red hot spot
	1500	93	7.1	($\cong$200)	*Bright* red spot
	2000	..	..	($\cong$300)	2, *yellow* hot spot
50 less focus voltage $\cong$43 on lens	1000	..	5.0	..	12
	1000	..	6.0	..	5
	1000	..	7.1	..	2, red hot spot
	1000	..	8.0	..	4, not red
	1000	..	9.0	..	10

voltages, due to the "cascading effect." The latter causes very high transient voltages to be impressed on subsequent sections if a tube-flash starts in one section. Such transients have extremely steep wave fronts. The electrodes of our multiple-section tubes are supported by the glass tube itself, with the metal parts so disposed as to prevent unduly high electric fields at metal surfaces adjacent to the glass, in spite of its high dielectric constant, and with spark-over in air between the tube-shields providing a "by-pass" of low impulse-ratio.

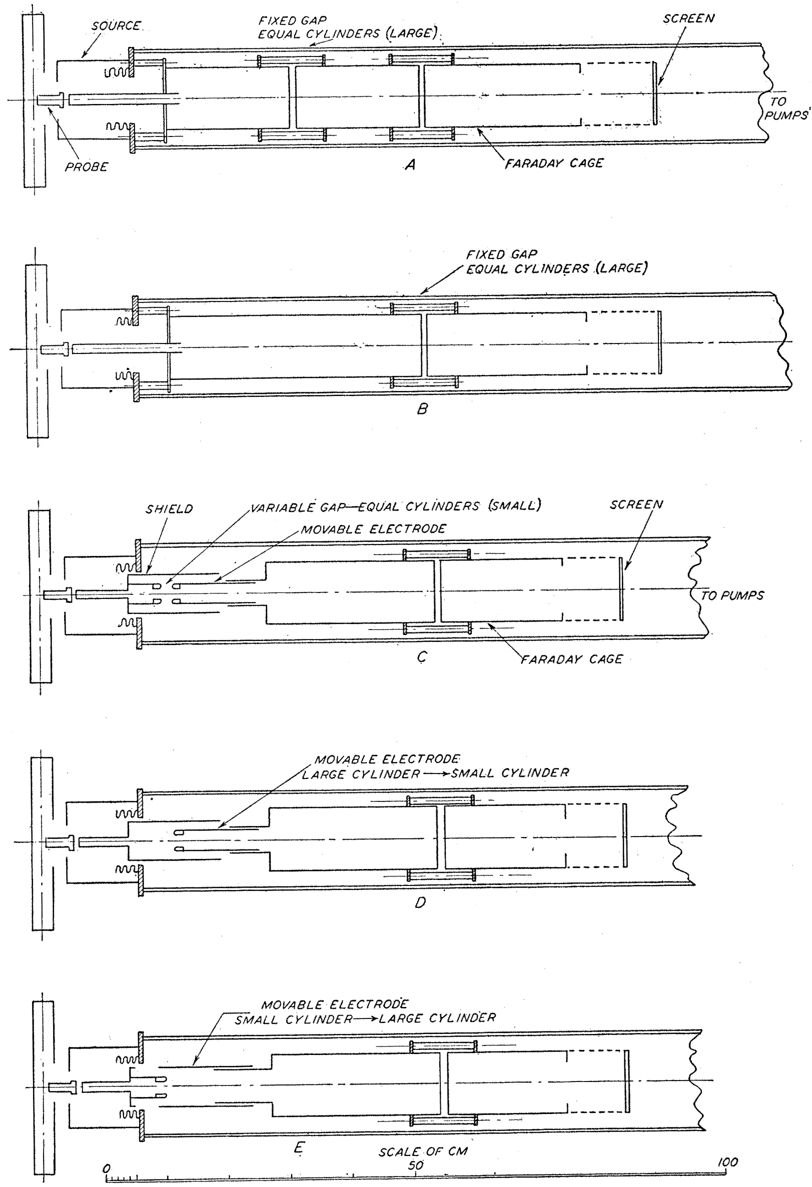

FIG. 9. Dimensions and positions of various electrodes used in tests of focusing effect of first tube gap.

gave 30 microamperes on the screen, but the "spot" spread over the whole screen and no adjustments gave any improvement. It was concluded that the distance was too great for a small diameter ion beam exceeding 10 microamperes at these voltages. In all of these tests at currents above 100 microamperes the ion beam was faintly visible in the tube beyond the tube lens, provided the voltages were set to make its diameter less than 10 mm.

(*b*) *Small diameter equal cylinders, variable spacing.* To determine the effect of variations in the diameter and spacing of the cylindrical electrodes used as the tube lenses, tests were next made, for the arrangement shown in Fig. 9*c*, with small diameter cylinders as electrodes one of which was movable by rack and pinion to vary the spacing or gap of the lens. The fluorescent screen was left at one meter from the arc capillary, but it was thought more nearly

TABLE X. *Observations on focusing with ion source lens and small diameter tube lens* (*case c of Fig. 9*). [Tube lens electrodes about 25-mm diameter (rounded), variable spacing or gap.]

Tube lens voltage (kv)	Gap between electrodes of tube lens (mm)	Probe voltage (volts)	Output current from probe (μA)	Required focus voltage (kv)	Faraday cage current (μA)	Description of spot
17 less focus voltage $\cong$12 on lens	4	2000	230	5.7	70	Hardly visible
	15	2000	230	5+	50	
	40	2000	230	4+	42	
	15	1000	28	5.2	22	
33 less focus voltage $\cong$23 on lens	2	2000	230	11.7	160	Red hot spot; annular rings; background
	7	2000	230	10.9	..	
	15	2000	230	10.0	..	Red; less background
	24	2000	230	9.5	160	Red
	40	2000	230	8.4	..	Yellow hot spot; no visible background
	15	1000	28	10.0	25	Very faint spot still focused
50 less focus voltage $\cong$40 on lens	4	2000	230	15	225	Red hot spot; strong background
	15	2000	230	13.5	225	Bright red spot; much less background
	24	2000	230	12	225	Yellow hot spot
	40	2000	230	11	225	Bright yellow spot
	15	1000	28	13.5	(40)	Still focused

correct for comparison with the 4-inch lens to have this smaller tube lens nearer the source, and it was placed at 20 cm instead of 40 cm as before. The measurements with this lens showed that these smaller diameter electrodes concentrated the total ion current from the source onto the screen nearly as completely as did the 4-inch electrodes, although below 50 kv both large and small lenses failed to focus the total current entering the tube for the higher currents. It is probable that there is no great difference between the two lenses as regards the completeness of focusing, both sizes focusing the total available current onto the target, but the smaller electrodes at close spacings gave definite evidence of worse aberrations, as indicated by the general background accompanying the focal spot. The aberrations are less at the larger spacings, which require a lower speed of the incident beam for the same focusing effect, the focusing effect of the lens itself being smaller at the wider spacings.

TABLE XI. *Observations on focusing with ion source lens and reentrant tube lens, from large cylinder into small cylinder* (*case d of Fig. 9*).

Tube lens voltage (kv)	Probe voltage (volts)	Output current from probe (μA)	Required focus voltage (kv)	Faraday cage current (μA)	Description of spot
50 less focus voltage $\cong$40 on lens	2000	230	10.3	160	Yellow hot, 2-mm. diam.
	1500	98	10.4	70	
33 less focus voltage $\cong$10 on lens	2000	230	7.2	110	Red hot
17 less focus voltage $\cong$4 on lens	2000	230	4.2	60	
	1000	28	4.1	25	

In general, these electrodes $1\frac{1}{4}$ inches in diameter have nearly twice the focusing effect of the 4-inch electrodes (require nearly twice the voltage on lens *FL* of the ion source to prevent overfocusing of the beam by the tube lens).

(*c*) *Reentrant electrodes.* Because of the possibility that reentrant electrodes might be desirable to shield the ion beam from deflection by charges on the glass walls of the high voltage tube, brief tests were made of two such arrangements, although the fact that closely spaced electrodes of large diameter also had been found satisfactory largely eliminated any possibility that reentrant electrodes might be necessary.

The arrangement of Fig. 9*d*, in which the ion beam is accelerated from a large cylinder into a small cylinder, was first tested. Although excellent (2-mm) focal spots were again obtained, the total output ion current did not reach the screen even at 50 kilovolts. The focusing effect of this arrangement (required "stiffness" of incident beam) was comparable to that of two equal cylinders the size of the smaller one used.

TABLE XII. *Observations on focusing with ion source lens and reentrant tube lens, from small cylinder into large cylinder* (*case e of Fig. 9*).

Tube lens voltage (kv)	Probe voltage (volts)	Output current from probe (μA)	Required focus voltage (kv)	Faraday cage current (μA)	Description of spot
50 less focus voltage $\cong$13 on lens	2000	230	13.4	185	Bright yellow, 2-mm diam.
	1500	98	13.3	75	Yellow
33 less focus voltage $\cong$9 on lens	2000	230	8.1	125	Bright red
	1500	98	9.0	70	Red; visible background

The reverse of this arrangement was also tested, the ion beam being accelerated from a small cylinder into a larger cylinder as indicated in Fig. 9*e*. This lens also appeared to give an excellent focal spot, although again focusing less than 100 percent of the probe canal output current.

(*d*) *Conclusions*. It is clear from the above tests that almost any arrangement of electrodes can be used with fair or even excellent success in a cascade type, multiple lens, high voltage tube, focusing most or all of the ion current entering the lens system onto a distant target *provided* the various voltages (including the ion source) are adjusted in relation to each other. Such considerations as the desirability for some problems of working with an ion beam spread uniformly over a comparatively large area (for example, 10-cm diameter) serves to indicate that electrodes of fairly large diameter are desirable, at least in the sections of the tube nearest the target. Again, if it is desired to apply a voltage of the order of 100 kv to the first section of the high voltage tube (nearest the ion source), it is also desirable to select fairly large diameter electrodes for this section (and those adjacent) in order that an inconveniently high voltage will not be required on the lens *FL* of the ion source to provide a beam of the requisite "stiffness" on entering the first tube lens.

(3) Successive lenses

Our knowledge of multiple lens arrangements is chiefly the qualitative information we have obtained during the past several years in using tubes having from 6 to 23 lenses for focusing ion currents up to 20 microamperes on distant targets at voltages from 200 to 1200 kv. That it is possible with such tubes to focus on the target all or nearly all of the ion current entering the tube, by proper control of the voltages applied to the first several lenses, already has been mentioned. In connection with the experiments described in this paper we have made only one set of observations with voltage applied to more than one tube lens. Using the arrangement of Fig. 9*a* with a potential of 70 kv on the tube lens nearest the ion source, currents up to 1000 microamperes were satisfactorily concentrated on a 3-mm focal spot on the screen. With 60 kv on the lens 700 microamperes was the maximum current which could be concentrated on the focal spot at the given distance and this current was correspondingly less at lower voltages. A second rectifier unit was then connected across the second tube lens, hitherto used as part of the Faraday cage for the target. Because of secondary electron emission the target currents were very unreliable, but it was interesting to find that when the ion source and first tube gap were left at given voltage settings, the indicated target current and the shape and size of the focal spot changed very little or not at all when the voltage across the second tube lens was changed from 10 kv to 65 kv. Some change in the brilliance of the focal spot was noticeable, due to the increase of 55 kv in the total tube voltage. This experiment again demonstrated the relative unimportance of the subsequent tube lenses after the ion beam has once attained an energy equal to or exceeding that corresponding to the voltage across a single tube lens. It also served to emphasize the importance of giving the initial ion beam the proper characteristics before introducing it into the lens system of the tube, since the focus voltage of the ion source continued to control the size of the focal spot.

The writers take pleasure in recording their indebtedness to Dr. F. L. Mohler and to Dr. C. M. Van Atta for their contributions to this work.