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THE PRODUCTION OF HIGH VELOCITY HYDROGEN IONS

WITHOUT THE USE OF HIGH VOLTAGES

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Introduction

The advancement of our knowledge of the structure of matter and its interaction with radiation depends to a large extent on studies of collision processes between atoms and swiftly moving ions and electrons. The greater part of our information on the structure of the atomic nucleus has come from experiments with high velocity alpha particles.[1,2] Apart from such studies with radioactive rays, experiments have been confined largely to impact processes involving kinetic energies of the order of magnitude of 100,000 volt-electrons or less. It would appear to be very important to develop an additional line of attack on problems of the nucleus by supplementing the alpha particles with sources of positive ions of equivalent or greater energies. It should be possible to develop a positive ion source of much greater intensity than the ordinarily available alpha particle sources. Such an ion source would yield high speed ions of controllable velocities and would have the added advantage of being free from the complicating effects of penetrating beta and gamma rays.

Moreover, the recent theoretical advances of the new wave mechanics, particularly concerning the nucleus, necessitate experimental verification, which can be done in many cases only by the use of particles of very high energies. For some problems positive ions are of much greater use than electrons. Both heavy and light ions would be useful in this study, but for the study of the atomic nucleus the lighter ions, particularly protons, are the most effective. We are guided in this statement by the recent theoretical work of Gamow on the "Theory of Artificial Disintigration".[3] By Gamow's theory the probability of an alpha particle of velocity v entering a nucleus of atomic number Z, after coming within the effective radius of the nucleus is

$$W = e^{\left(\frac{-16\pi e^2 Z J_k}{h v}\right)}$$

where J_k is a function varying slowly with v and Z. It is clear, therefore, that for particles of equal energy the lighter particle has the greater chance of penetration into the nucleus. Also, since the charge on the proton is only half the charge on the alpha particle, its potential barrier will be half that for the alpha particle.[4,5] So we would choose protons as the most effective of positive ions for these reasons. It should be noted that for most impact processes, especially those involving the use of thin foils, hydrogen molecular ions, H_2^+, would be very little different than two protons travelling with the same velocity. This is due to the breaking up of the molecular ion after passing through the fields of force of relatively few atoms as it enters the foil.

The two main difficulties in the production of such particles of high energy are the production of the very high potentials necessary to accelerate the particles and the development of vacuum tubes capable of withstanding these voltages. Before the year 1930 very little had been published on this subject. W.D.Coolidge[6] developed the cathode ray tube to withstand as high as 350,000 volts and brought the rays out through thin metal windows. He later increased this to 450,000 volts and by placing three tubes in series has been able to produce 900,000 volt electrons.[7] C.C.Lauritsen and R.D.Bennett[8], using the powerful "cascade" system of transformers in the California Institute of Technology high voltage laboratories, have developed a high potential X-ray tube capable of operation at 750,000 volts. They are at present developing the method with the hope of reaching 2 million volts.

The year 1930 has brought out several publications by other experimenters in the field, due to the impetus given the problem by the predictions of the new wave mechanics. Using a Tesla-coil mounted in oil under pressure, M.A.Tuve, L.R.Hafstead and O.Dahl[9] have produced voltages of approximately 5 million volts. They have successfully applied voltages up to 1.4 million volts to a vacuum tube of special design, applying small portions of the total potential drop to short sections of the tube, and have obtained artificial beta and gamma rays corresponding to a peak of 1.3 million volts. Work is now in progress on the acceleration of protons to radioactive speeds.[10] Using a similar method, A.Brasch and F.Lange[11] have independently produced and applied to a vacuum discharge tube voltages up to 2.4 million volts and have obtained and measured the intensities of X-rays corresponding to this peak. Apart from radioactive sources, experimental investigations with positive ions have been limited to much lower voltages. Chr. Gerthsen[12] used canal rays with energies up to 51,000 volt-electrons to study many of the problems of scattering, energy-loss and ionizing ability of the rays. J.J.Cockroft and E.T.S.Walton[13] have produced hydrogen ions and protons with energies up to 280,000 equivalent volts and have obtained evidence of 40,000 volt X-rays from the ions.

All of these methods involve equipment so elaborate and expensive as to be prohibitive for most laboratories. The difficulties of insulation and protection against corona losses at such high voltages are enormous. Large, expensive and dangerous high voltage laboratories are required. The necessity of having tools to investigate the atomic nucleus and check the theories advanced by the new wave mechanics is apparent. The most efficient tools for this purpose would be positive ions of small molecular weights and very high energies. It is clear that there is great need for some comparatively simple and inexpensive method for the production of such high velocity ions, preferably without the use of high voltages. This paper gives a report of the essential experiments in the development of just such a method, in which hydrogen ions have been accelerated to high velocities without the use of high voltages, and indicates how this method is to be extended to supply a source of such particles with radioactive energies. The method eliminates most of the difficulties and a great deal of the expense of the other methods described by not necessitating high voltages and should prove of great value in the study of this extremely interesting field of high energy impact processes.

The Theory of the Method

The fundamental principle of this method is concerned with the resonance of a charged particle with a high frequency oscillating electric field. At present in this laboratory we are developing two complementary methods which use this principle but apply to different types of particles. The method used for heavy ions is to accelerate a beam of such ions through a series of metal tubes arranged in line, and attached alternately to the two ends of the inductance of a high frequency oscillatory circuit. The tubes are made successively longer (proportional to the square roots of integers) so that the time of passage through each tube is a constant, equal to the half-period of the oscillating circuit. During the time a particle takes to travel through one tube the electric field between successive tubes has changed direction, so that the particle experiences a force in the same direction each time it passes from one tube to the next. The ion arrives at the end of the series of tubes with an energy which is equivalent to the sum of the potential drops through which it has passed. This method is applicable only to fairly heavy ions; for light ions and electrons the tubes would be so long as to make it impractical. R.Wideroe[14] originally demonstrated this method, and at present it is being developed in this laboratory by E.O.Lawrence and D.H.Sloan[15] using mercury ions.

The method used for light positive ions, which is reported in this paper, also uses the resonance of the ions with an oscillating electric field, but overcomes the difficulty of the long series of tubes used in the preceding experiment by "spinning" the ions by means of a magnetic field around inside two hollow plates which are connected to the oscillatory circuit. The principle of this method was briefly given by E.O.Lawrence and N.E.Edlefsen[16] in a paper presented before the National Academy of Sciences.

An elementary description of the process may be given by considering two "duants" or hollow semi-circular plates, mounted symmetrically with their diametral edges facing each other and closed by grids, forming inside each plate a field free space (Fig. 1). These plates are connected across the inductance of a high frequency resonant curcuit and mounted in a vacuum between the poles of a large electromagnet with a uniform field strength over the region of the plates. If an ion finds itself in the space between the grids a and b at an instant when the electric field is a maximum in one direction, it will be attracted to the grid of opposite charge. For instance, consider a hydrogen molecular ion, H_2^+, If plate A is negatively charged the ion will be attracted to it, gaining a velocity from the field and passing through the grid a into the field free space inside plate A. Under the influence of the strong magnetic field H at right angles to its path, the ion will travel in a semi-circular path inside the plate A, eventually arriving at the grid a and again passing into the space between the grids. Now referring to the time variation of the high frequency current, Fig. 2, it is seen that if the initial impulse is imparted at time t_1, and the particle arrives back between the grids at time t_2, exactly ½ cycle later, it will find the field between the grids reversed and will experience an acceleration toward grid b. The time required for the particle to travel a semi-circular path inside the plate A is the same for all velocities. This becomes clear when it is recalled that the radius of the circular path on which the ion travels is proportional to its velocity. Therefore this process continues, and for the resonance condition described above the particle gains velocity with each passage through the region between the grids until it arrives at a collector placed at the outer edge of the tube.

The two forces acting to keep the ion in equilibrium while traversing this path are the centrifugal force due to its circular motion and the force due to the magnetic field. A charged particle moving with a velocity v in a magnetic field H experiences a force at right angles to the direction of its motion and to the magnetic field, given by the relation

$$F = \frac{H e v}{c} \qquad (1)$$

where c is the velocity of light and e the charge on the particle. The centrifugal force due to the motion of a particle of mass m in a circle of radius r is

$$F = \frac{m v^2}{r} \qquad (2)$$

Equating, we obtain

$$\frac{m v}{r} = \frac{H e}{c} \qquad (3)$$

The frequency relations are

$$f = \frac{c}{\lambda} = \frac{v}{2\pi r} \qquad (4)$$

where λ is the wave length and f the frequency. Substituting Eq. (1) in a modified form of Eq. (4) we obtain

$$f = \frac{v}{2\pi r} = \frac{m v}{r}\frac{1}{2\pi m} = \frac{H e}{c}\frac{1}{2\pi m} \qquad (5)$$

Thus we get for the two fundamental equations

$$f = \frac{H}{2\pi c}\,\frac{e}{m} \tag{5}$$

or

$$\lambda = \frac{2\pi c^2}{H}\,\frac{e}{m} \tag{6}$$

These relations, Eqs. (5) and (6), are seen to be independent of the radius of path r and of the velocity of the particle v. The energy received by a particle of charge e and mass m in falling through an electric field V (in volts) is

$$\tfrac{1}{2} m v^2 = \frac{V e}{300} \quad \text{or} \quad v = \sqrt{\frac{2V}{300}\,\frac{e}{m}} \tag{7}$$

Using Eq. (5) we get

$$\frac{v}{2\pi r} = \frac{H e}{2\pi m c} \quad \text{or} \quad r = \frac{c\,m}{H\,e}\,v$$

$$r = \frac{c}{H}\sqrt{\frac{2V}{300}\,\frac{m}{e}} \tag{8}$$

Inverting this, we find the voltage equivalent to a radius r and a magnetic field H to be

$$V = \frac{H^2 r^2}{c^2}\;\frac{300}{2}\,\frac{e}{m} \tag{9}$$

This expression gives the value of the total voltage acquired by the ion when it arrives at the collector, if we take r to be the distance from the center of the tube out to the collector. For a particle of given mass and charge this final value of the voltage is proportional to the square of the magnetic field and the square of the radius of the tube and therefore is directly determined by the dimensions and strength of the magnetic field.

The constants used in solving these equations are:[17]

m (proton) = 1.6606×10^{-24} gm

e (electron) = 4.770×10^{-10} ab. esu

c (velo. light) = 2.99796×10^{10} cm/sec e/m (electron) = 5.303 x 10^{17} ab. esu

e/m (proton) = 2.875 x 10^{14} ab. esu

e/m (H_2^+ ion) = 1.4375 x 10^{14} ab. esu

e/m (He^+ ion) = 0.7187 x 10^{14} ab. esu

r (radius of tube to collector) = 4.50 cm = 1.77 in.

On substituting the proper values in Eq. (4) we get the numerical relations:

Protons: H λ = 1.966 x 10^7

H_2^+ ions: H λ = 3.932 x 10^7

He^+ ions: H λ = 7.864 x 10^7

These curves are hyperbolas and are the theoretical curves for the fundamental resonance conditions of the ions named. They are plotted on Fig. 6 with the wave lengths λ as ordinates and the magnetic fields H as abscissas.

Eq. (8) is used to compute the radii of the successive semi-circular paths of the ions in the magnetic field for a given oscillator voltage. From this the total length of free path necessary may be calculated, thereby providing an estimate of the necessary pressure of hydrogen in the tube.

If we use the value given above for maximum radius of the tube in Eq. (7) we get a relation for the final voltage of the ions at the collector as a function of the magnetic field applied. This is plotted on Fig. 7 for protons and H_2^+ ions and serves to predict the expected ionic energies, in terms of equivalent volts.

The possibility of a secondary resonance condition, is an interesting outcome of the theory. Referring again to Figs. 1 & 2, if an ion receives its initial impulse at time t_1, under a comparatively low value of magnetic field it may describe a larger semi-circular path, taking more time, and arrive again between the grids at the time t_3. This corresponds to resonance with a frequency of 1/3 the fundamental or a wave length of three times the fundamental, and correspondingly we find the magnetic field to be 1/3 that required for the fundamental resonance condition. The experimental curves which follow show this effect clearly.

A very pertinent question is that regarding the action of electrons from the filament and from secondary processes in the tube. A short calculation shows that for magnetic fields of the order used, the resonant wave length would be of the order of 0.33 cm, and the radius of path a maximum of 0.5 mm. Electrons in the tube would travel down the lines of magnetic force to the sides of the tube in spiral paths not more than 0.5 mm in radius, and so would never interfere in any way with the resonant processes. In fact this does have one decided advantage in that it collimates the electron beam from the filament and forces it to proceed straight across the tube between the grids, which is most advantageous in producing ionization of the hydrogen in the proper place to be effective.

Design

The essential features to be provided for in the design of a tube to study this phenomenon may be enumerated as follows:

1. Two semi-circular hollow plates closed by grids of such design as to allow the particles to pass through them unobstructed, yet giving a uniform electrical field between them and at the same time insuring the field free condition inside each plate.
2. A flat vacuum tight outer tube of not more than one inch thickness to enclose these plates, and a suitable vacuum pump.
3. A large electromagnet with a uniform field over the region of the plates, between the poles of which this tube is to be placed.
4. A high frequency oscillator set, providing sufficient power to give the necessary voltages on the plates, arranged so that the frequency will be variable.
5. A filament to send a beam of electrons between the grids which will not be affected by the high magnetic fields and which will give electron currents of the order of magnitude of 20 mils.
6. A collector to catch the high velocity ions at the edge of the magnetic field and also devices to measure their energies.

The metal tube used in these experiments is designed to meet all the requirements. See Fig. 3. A ring of seamless brass tubing is fitted with brass sides to form a hollow flat tube. Inside this is mounted a semi-circular hollow plate so as to be suspended in place without touching the sides of the outer tube. A copper to glass seal assembly gives sufficient rigidity and insulation. The opposite half of the outer shell is itself the other plate. The two grids are mounted parallel to each other far enough apart to give sufficient insulation and yet close enough to make the time during which a particle is between the grids small in comparison with the total time of its circuit. An oxide coated filament with an internal heating unit is mounted on the fixed grid at the extreme side of the tube, directly over a slot mounted on the suspended grid, so as to direct the stream of electrons between the two grids. A window for viewing the filament and the general ionization in the tube, a large outlet to the pumps and an entrance for hydrogen diametrically opposite it are properly placed on the outer brass ring. The collector system consists of a Faraday cage with a 2 mm slit in the front face, a grid of fine wires for applying retarding potentials, and a pair of plates for applying deflecting potentials; this whole system is carefully shielded and the beam is defined by a slit system concentric with the tube.

The grids are an important item in the design. Originally they consisted of two 1/16 inch brass plates in which many small holes had been drilled so as to leave the proportion of metal in the face of the grid very small (only about 1/5 the total area). These holes were drilled in rows and the rows staggered in order to reduce the amount of metal remaining between them. The first experiments showed this type of grid to give results, but the intensity dropped off rapidly as the number of revolutions in the tube was increased. This was due to the cutting out of 1/5 of the beam each time it passed through a grid. A calculation of the fraction left in the original beam after 15 revolutions showed that only 0.001 of the original intensity remained. The final design uses a system of parallel saw slots, very close together and parallel to the plane of rotation of the ions. Neglecting the existence of small sideward velocities, due to contact potentials, initial thermal velocities, etc., an ion will revolve in the same plane until it reaches the collector, and so will pass through the same slot in the grids each time thereby eliminating the above difficulty. Since it is known that contact potentials may exist in a tube of this kind of the order of magnitude of a volt, there is a possibility that the ion would be pulled sidewards enough to make it strike one of the thin divisions between saw slots before it gets to the collector. An approximate calculation shows that transverse potentials averaging less than 0.1 volt over the tube would be sufficient to deviate the beam through the width of one saw slot after 20 revolutions. The fact that the experimental results show that the ions travel around many times indicates that even though these potentials exist, their effects are averaged out along the paths of the ions and we may conclude that the slotted grid design is effective.

The filament used in the final arrangement of the tube is an oxide coated radio tube filament, designed for use in alternating current tubes. It consists of a U shaped tungsten filament threaded through two holes drilled lengthwise through a clay tube, around which is an oxide coated nickel cylinder. This arrangement prevents any motion of the filament wires in the powerful magnetic field and gives a large emitting surface. The dimensions are 2 mm outside diameter and 2 cm total length.

The high frequency oscillator set uses two 75 watt "852 Radiotrons" in parallel, "Navy" box type condensers, and coils of various sizes wound to give the desired wave lengths. The "B" supply was obtained by the use of two kenotron tubes to give full wave rectification of the output of a "pole" transformer giving 10,000 volts maximum. Usually a small variable condenser was placed in parallel with the tube across the inductance in order to give rapid changes of frequency if desired. The power available is much greater than that needed for most of the experiments.

In pumping out a metal tube with wax joints a very fast vacuum system is necessary. The final system consisted of an ordinary mercury vapor pump connected to the tube through short lengths of large diameter tubing (1.25 inch) and through a liquid air trap of the same diameter. A Cenco Hivac oil pump was used as a fore-pump. Dennison's red sealing wax was used for sealing the tube, and was found quite satisfactory.

Hydrogen was generated electrolytically, stored in a large reservoir and let into the system through a calcium chloride drying tube, a liquid air trap and a long capillary tube. The pressure of hydrogen could easily be controlled by the size of the capillary and the pressure in the storage reservoir. The pumps were kept running continuously and the hydrogen allowed to pass continuously through the tube.

Two magnets were used in the course of the experiment. A rather small magnet giving only about 5500 gauss maximum over the area of the tube was used for the larger part of the studies reported. A larger magnet*, available for a short time, was used to extend the readings of resonance effects up to its limit of nearly 13,000 gauss over the same area. This larger magnet was not available for detailed studies at this higher range however. In each case the magnets were calibrated by the use of a ballistic Grassot fluxmeter, which in turn was calibrated by the usual method of reversing a known current through a solenoid of known dimensions and computing the flux change. These calibrations gave relatively accurate curves which, however, due to the crudity of the apparatus available were not accurate in absolute value. This difficulty was overcome by finding accurately the position of one of the resonance peaks, computing the corresponding magnetic field and shifting the scale of the magnetic field calibration slightly to bring this point on the curve. As the experimental results show, (Fig. 6) all the other resonance peaks lie quite accurately on the curve, justifying this method of calibration.

An elementary calculation of the total length of path necessary for the H_2^+ ions (Eq. (8)) shows that 300 cm is a fair estimate. Using the simple mean free path relation

$$L = \frac{1}{\pi N \sigma^2} \qquad (10)$$

where N is the number of ions per centimeter cubed at the desired pressure, σ the radius of collision which is equal to $\frac{1}{2}$ the diameter of the hydrogen molecule; and using the expression

* Appreciation is due Dr. Robert E. Holzer for his generosity and patience in interrupting his own research to allow us the use of his large magnet for this purpose.

relating pressure to density

$$N = \frac{6.06 \times 10^{23}}{22.4 \times 1000} \times \frac{P}{760} \qquad (11)$$

where P is given in mm of mercury, we can calculate the mean free paths for various pressures to be:

2×10^{-4} mm of Hg.	= 77.8 cm
1×10^{-4} mm of Hg.	= 155. cm
5×10^{-5} mm of Hg.	= 310. cm
2×10^{-5} mm of Hg.	= 775. cm
1×10^{-5} mm of Hg.	= 1550. cm

Estimating the pressure drop between the tube and pressure gauge, which is outside the tube, to bring in a factor of $\frac{1}{2}$, we see that the pressure of hydrogen in the tube must be of the order of magnitude of 2×10^{-5} mm of mercury. It is interesting later to see how the experimental results check this approximate pressure prediction.

The pressure gauges used were two, a McLeod Gauge for measuring fairly large pressures (calibrated in the usual way), and an ionization gauge calibrated with reference to the McLeod and also by means of calculations from the literature. This gauge was mounted very close to the tube to give a fairly accurate measure of the pressures inside.

Results and Discussion

The first type of readings taken was with an unshielded flat plate for a collector at a distance of 4.50 cm from the center of the tube. A typical curve of this type is shown in Fig. 4. This curve is believed to be a composite of many effects, chief among which is that due to a general ionization throughout the tube and the accompanying photoelectric emission from the plate. The general ionization in the tube is explainable in terms of a "quarter-cycle effect", in which ions passing only once through the potential drop between the grids travel through only one quarter of a full cycle and arrive at the collector. This necessitates the supposition that the ions leave the grids at all angles, not necessarily at right angles to the grids which is the assumption in the case of the resonant ions. The magnetic field which would just allow these particles to traverse a path carrying them out to the grid is that which would give the greatest effect. This would depend on the oscillator voltage, and Fig. 4 shows this effect to be obtained experimentally. Referring to the computations which gave Fig. 7, we see that ions with voltages equivalent to only one impulse of the electric field (say 500 volts) will reach the collector, which is at a distance of 4.50 cm, in a magnetic field of approximately 1000 gauss, which is the value of the magnetic field for the maximum of Fig. 4.

With the development of the collector shown in Fig. 3 with its careful shielding and narrow slit system, more definite results were obtained. The slit system made it necessary for the ions to be travelling in paths with radii equal to the 4.50 cm distance to the collector before they could enter. With this arrangement peaks were found in the electrometer vs. magnetic field curves, the highest one of which in general corresponded to the computed resonance magnetic field. A typical curve of this type is given in Fig. 5. Three peaks are noted on this curve. Peak A we will find later subdividing into two peaks each of which has a distinct meaning, but at present we will explain it as due to the same quarter-cycle effect previously mentioned. This peak does not vary with frequency but does vary with oscillator voltage, exactly in the same manner as explained relative to Fig. 4. Two experiments were tried to test this theory. The magnetic field was reversed, and it was noted that the only part of the curve left was this first peak which was the same as before. This indicates that the peak is not due to a resonance effect but to some general ionization in the tube. Also this shows that the peak is probably not due to positively charged ions. Another test was that of substituting a solid grid for the slotted one on the internal suspended plate. The results here showed the same thing, only this first peak and no resonance effects at all, which is to be expected. Peak C, although at this early stage hard to classify, proves to be a general background hump persisting through all the curves but easily controlled by certain conditions. It proves to be composed of relatively low velocity particles, probably due to the results of secondary collisions in the tube and to particles not quite in resonance but nevertheless getting around through the grids several times. It is to be noted that particles may be out of resonance as much as 20% and still go through the grids 5 times, or as much as 10%

and still go through 10 times. Peak D is the true resonance peak, always much sharper then the others and usually higher. This sharp peak occurs for each wave length used at the value of magnetic field predicted by the resonance equation, Eq. (6), the curve of which is plotted on Fig. 5. Experiments were made, varying the wave length of the oscillator and measuring the position of the peak in each case, extending over the whole range of the two magnets available for the work. The resonance conditions were easily obtained at the highest values of magnetic field used, which was nearly 13,000 gauss, and produced ions which, if true high velocity particles, would have energies of nearly 80,000 volt-electrons. Below are tabulated the readings obtained for the magnetic fields of resonance over the entire range of wave lengths used. These points are plotted on Fig. 6 and show as the small crosses, which are seen to be in close agreement with the theoretically computed resonance curve.

λ (meters):	H (gauss):	λ (meters):	H (gauss):
180	2200	63.0	6350
162	2400	60.0	6700
150	2460	53.5	7150
120	3330	51.5	7750
100	3800	50.0	8300
100	3850	47.2	8500
88	4500	42.0	9250
80	5050	38.0	10300
76	5200	36.0	10800
70	5700	32.0	12200
67	6050	31.5	12400
66	5950	31.0	12700
64	6250		

In the more thorough study to follow it was necessary to use the small magnet and investigate only within its range. However, the close similarity of the types of curves obtained, and the theoretical reasons for assuming the continued existence of the resonance effect up to the high magnetic fields, make it possible to assume that the detailed study of the process for lower magnetic fields is in no essential respects different than that which would be obtained at the higher fields. So we go on into the study with the belief that these are typical cases.

A great number of variables enter into the process, among which are the wave length, magnetic field, hydrogen pressure, retarding potential, oscillator voltage, deflecting potential, potential of the collector, etc. The effect of variation of wave length on the position of the resonance peak of the current-magnetic field curve has already been noted. The peak indicating the fundamental resonance condition shifts its position, varying inversely with the wave length, and is found to check closely the calculated positions. Next is taken up the variation of the effect with the pressure of hydrogen in the tube. (Fig. 8) It has been mentioned previously that an estimate of the pressures necessary in the tube gives the figure of 2×10^{-5} mm of Hg as that which would give sufficient hydrogen for ionization and yet an adequate mean free path for the ions. The solid line curve, which appears to be an optimum value of hydrogen pressure, is that obtained for a pressure of 2×10^{-5} mm of Hg, checking the predicted value. In order to obtain curves free from background effects to a considerable extent, a retarding potential of 1000 volts was applied to the proper grid in front of the collector. This potential acts to cut out the particles of low velocity, and this becomes more apparent in the discussion to follow. In Fig. 8 the pressures lower than 2×10^{-5} mm show greatly reduced intensities due to the decrease of the number of hydrogen molecules available for ionization. Above this optimum value we find the background hump C rising rapidly, which is to be expected for several reasons. First, the shortening of mean free paths of the ions to less than the total spiral path of the ions in the tube introduces a greatly increased possibility of collision. Second, due to this shortening mean free path for resonant ions, the other ions produced out of resonance, which in general travel much shorter paths, will have a relatively greater intensity. When the available supply of hydrogen is increased these non-resonant ions will increase much more than the resonant ions. At the highest pressure of 10 x 10^{-5} mm the peaks broaden considerable and the background effect is very great, indicating an increasing number of secondary collisions in the tube. Peak A may still be explained by the quarter-cycle effect, but it appears now to be due entirely to photoelectric emission from the collector. The reason for this statement is that the peak is completely cut out by a few volts (3 or 4) of positive potential on the collector. The position of this peak, however, is most certainly due to the same condition of general ionization in the tube mentioned previously, in which soft X-rays and similar exciting radiations are given out throughout the tube. So this peak may still be called the quarter-cycle effect peak. Peak D is the true fundamental resonance peak, and shows a very sharp condition of resonance. Peak B is the harmonic resonance peak, or triple wave length peak, which is expected from the theory and is found precisely at the place predicted. For high pressures it is of greater intensity than the resonance peak D, probably due to the fact that the particles have a much shorter path to transverse. The fact that the resonance peak maintains approximately the same intensity for a good share of the pressure range indicates only that there is a certain balance between the tendency to be decreased by collisions as pressure increases and the tendency to increase due to the increasing number of ions available.

A set of current-magnetic field curves showing the variation of oscillator voltage with other variables kept constant is given in Fig. 9. Peak A broadens considerably with slight increase in voltage, and the quarter-cycle effect still serves to explain it. The resonance peaks B and D decrease considerably with decrease in oscillator voltage, but this is consistent with the theory in that the resonant ions must go through the grids many more times and so travel much longer paths as the voltage is lowered. They arrived at the collector with the same final voltage, however, and this method of variation serves as a method of obtaining the maximum amplification factor of the tube. We find from Fig. 7 that the final voltage is approximately 10,000 volts. Dividing this by the minimum applied voltage under which any resonant peak is observed, which is 200 volts, we find an amplification of 50, meaning 25 complete revolutions in the tube.

Fig. 10 gives the current-magnetic field curves obtained by variation of the retarding potential on the grid in front of the collector. Potentials up to 1000 volts only were obtainable, but they show the salient characteristics. Peak A is as before the quarter-cycle effect. The fact that it is not cut out by the retarding voltage indicates the existence of some sort of radiation to excite it and so checks our previous theory of secondary emission from the collector. Peak B, which proves to be of final velocity equivalent to about 1000 volts (referring to Figs. 6 and 7 as before) is completely cut out by the retarding potential of 1000 volts. The background hump proves to be of less than 1000 volts, and seems to contain bands or peaks of different voltages, probably due to some more complicated processes involving the geometrical shape of the tube. The resonance peak D, supposedly of 10,000 volt-electrons of energy, easily goes through the maximum retarding potential. The fact that this peak does not decrease to any great extent with increase of retarding potential shows that it is made up almost entirely of high velocity particles, at least higher than 1000 volts. All of these results then are in accord with the expectations.

A test which is apparently crucial in measuring the velocities of the ions is that of varying the deflecting potentials on the set of plates provided for that purpose in front of the collector. Fig. 11 gives these curves. The general decrease of intensity of the resonant peaks as the deflecting potential is increased may at first sight appear inconsistent with the supposition that these peaks consist of high velocity particles. This is explained by a consideration of the geometrical arrangements of the collector system. The slits are wide (5 mm) and the beam of ions is by no means perfectly collimated. So as this wide beam is swept across the collector opening by increasing the deflecting potential, the intensity would be expected to decrease considerably, even though a large proportion of the ions of the beam are true high velocity ions. The efficient action of a pair of deflecting plates in measuring voltage depends on the true collimation of the beam of particles being measured. In this tube it is almost impossible to obtain this collimation and yet retain sufficient intensity to measure. However, the essential features of the curves on Fig. 11 are still in accordance with the theory that the ions of the resonant peak are high velocity ions. The background C disappears with much lower deflecting voltage, indicating much lower velocity ions. The harmonic resonance peak B is seen to disappear before the resonance peak D as the potential is increased, also indicating lower velocities. The peak A deserves special consideration here, for this peak is again completely cut out by a few volts of positive potential on the collector. The fact that the intensity of Peak A decreases with application of deflecting voltage seems to indicate the possibility that many of the collisions in the tube which give off the exciting soft X-rays occur in the region between the deflecting plates. The resonance peak D still shows considerable intensity for deflecting voltages as high as 550 volts, and yet 700 volts cuts it out completely. Taking 600 volts as an estimate of the deflecting voltage just required to cut out the beam, we can calculate the corresponding velocity. The relation as derived for parallel deflecting plates comes out to be

$$V = \frac{k L^2 D}{4 d h}$$

where V is the equivalent velocity (in volts) of the ions, D the deflecting potential, L the length of the plates, d the distance between them and h the width of slit, or the distance the beam must be moved to be just cut out at the end of the plates, and k is a constant depending on the distance of the collector slit from the end of the deflecting plate system. Since this distance is roughly equal to $\frac{1}{2}$ the length of the plates, we take this constant to be 2. Also L = 1,7 cm, d = 0.5 cm, h = 0.2 cm. So we find:

$$V = 14D = 14 \times 400 \text{ volts} = 8400 \text{ volts.}$$

This result is of the right order of magnitude and indeed since the measurements of the tube dimensions are somewhat inaccurate we can consider it a good check of the expected value of 10,000 volts. This makes it justifiable to state that the voltages obtainable with this method are of the order of magnitude of and probably equal to those calculated from the theory.

The highest amplification factor obtained in this tube is calculated from Fig. 12. In this case the wave length was changed to 76 meters, bringing the magnetic field for resonance very nearly at the top of the magnet calibration curve, or at 5200 gauss. It was found that an observable resonance peak was obtained with an oscillator voltage of 160 volts. The peak corresponds to a maximum final voltage of 13,000 volts. This gives an amplification factor of 82 and means that the particles have made 41 complete revolutions in the tube. The velocities of the ions at higher magnetic fields are considerably greater and the transverse components of velocity of lesser importance. This, and the experimental fact that the amplification factor appears to be larger for higher magnetic fields, makes it certain that the amplification factor for fields up to the maximum used in the experiment is at least as large as 82 and possibly larger.

It should be possible to obtain similar resonance effects for protons. During this experiment small peaks have been observed several times which corresponded with the calculated position for the proton peak. However, these observations were not definite enough to make any statement regarding them. At these low pressures, and with the type of ionization process used in this experiment, the relative number of protons produced would be very small and probably unobservable.[18,19] However, with the development of a more efficient source for protons it should be possible to obtain resonance effects entisely similar to those obtained for hydrogen ions.

Accuracy

The magnetic field calibrations are relatively accurate to about 2 %, and the measurements were always taken in the same way in order to eliminate any hysteresis change. The absolute accuracy of the magnetic field calibration curves is, as mentioned previously, determined by the resonance conditions of the experiment. The collector slit is quite wide, and so the measurement of radius of the tube is necessarily vague. Since the final voltage obtainable is proportional to the square of this radius, the error is probably not less than 10 % for this tube. This can easily be lowered as soon as increased intensity justifies the narrowing of the slit. The error involved in reading the magnetic field current meter is as much as 3 %, which in itself is sufficient to cause the deviations of the experimental points from the curve of Fig. 5. The fluctuations of line voltage of the 110 volt A.C. line were amplified considerably by the oscillator set, and produced fluctuations as high as 5 % in the electrometer readings. However these fluctuations are proportional to the magnitude of the reading and the curves are relatively much more accurate. The fluctuations are not sufficient to hide the essential features of the curves. They must not, however, be interpreted as mathematically accurate. In general we may say that Fig. 5 indicates a relative accuracy which is well within the limits of experimental error, but that the method has not been developed to the point where it is important to obtain a high absolute accuracy.

Conclusion

The experimental results may be summed up as follows:

1. The method is successful in obtaining the resonance effects predicted by the theory.

2. Hydrogen ions have been produced with energies of the order of magnitude of 80,000 volt electrons from low voltage, high frequency oscillations of the order of 2000 volts.

3. Studies have been made which prove that the particles in the resonant beam consist of ions with velocities of the order of magnitude of those predicted by the theory - true high velocity ions.

4. A maximum amplification of 82 has been obtained.

A general consideration of these experiments shows that the method is eminently satisfactory for the production of high speed hydrogen ions and indeed indicates that it is possible to produce ions in this way limited only by the magnetic field available. These appear to be no fundamental difficulties in the way of obtaining particles with energies of the order of magnitude of one million volt-electrons. At present there is under construction an electromagnet capable of producing hydrogen ions of $\frac{1}{8}$ million volt-electrons of energy or protons of one million volt-electrons of energy.

It is a pleasure to acknowledge my indebtedness to Prof. E. O. Lawrence for suggesting the problem and for offering valuable advice and assistance throughout the course of the experiment.

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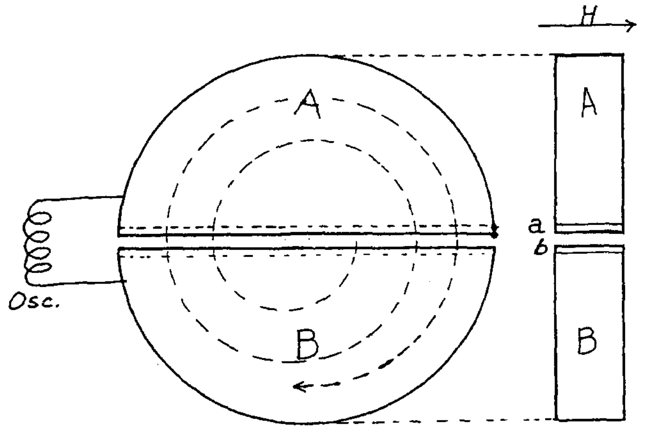

Fig. 1

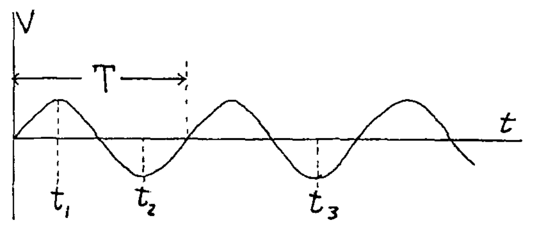

Fig. 2

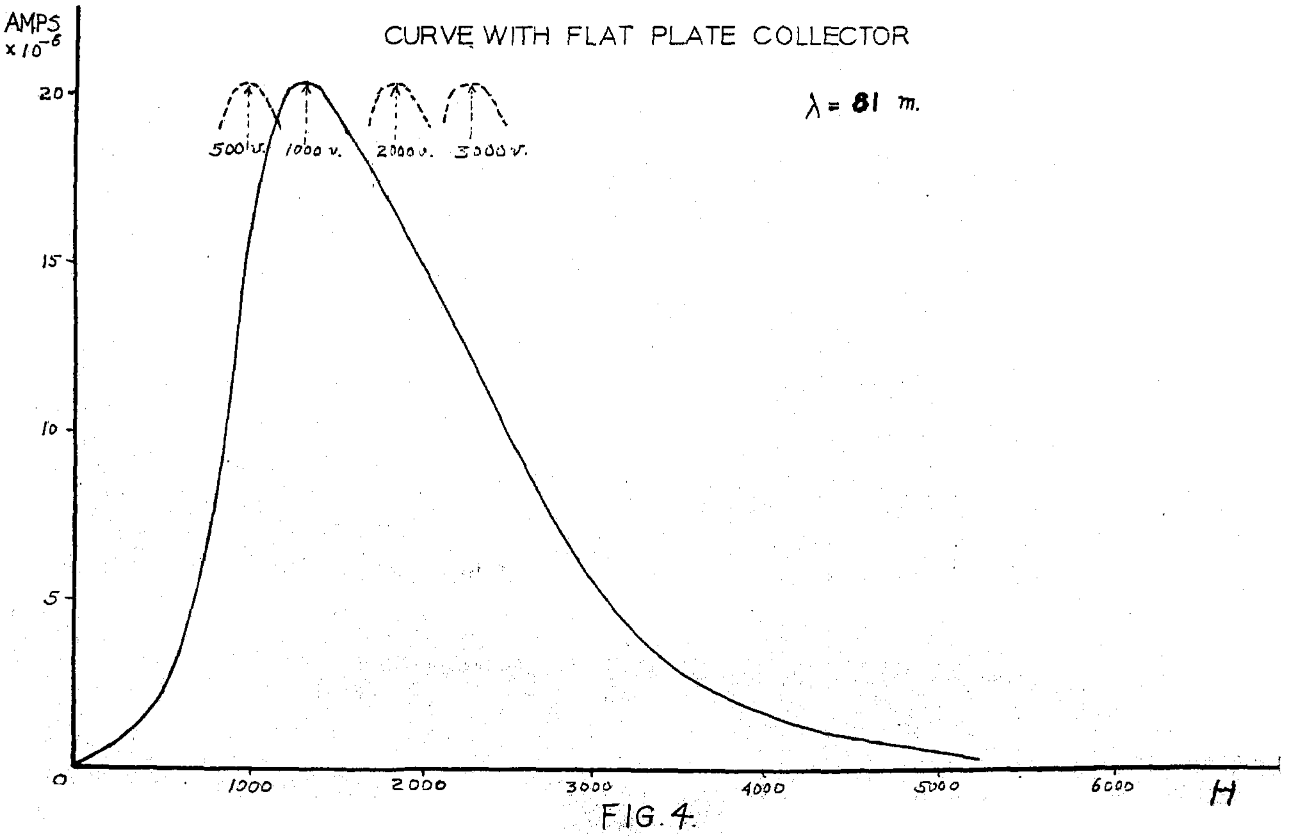

FIG. 4.

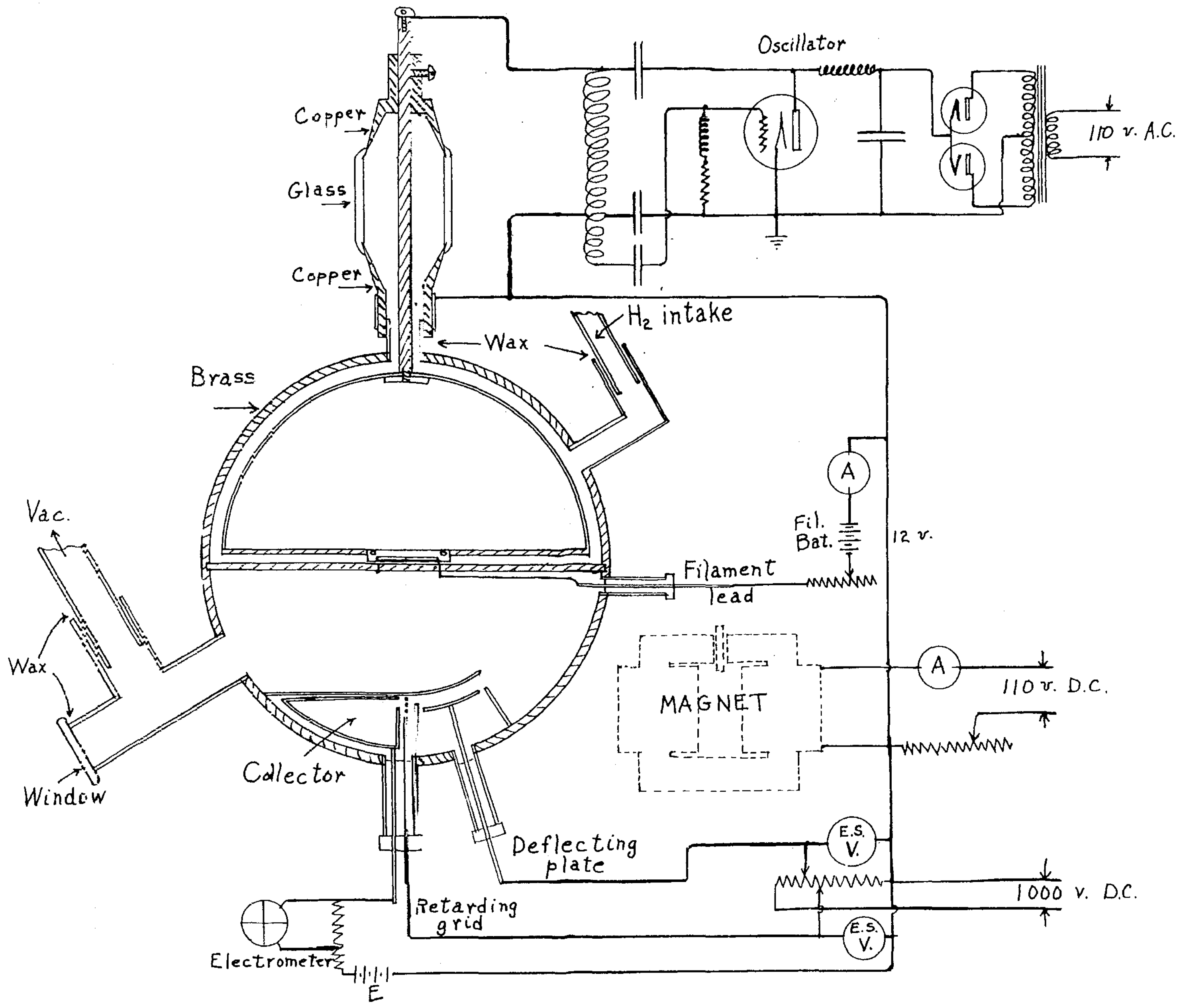
Oscillator
110 v. A.C.
Copper
Glass
Copper
H_2 intake
Wax
Brass
Vac.
Wax
Window
A
Fil.
Bat.
12 v.
Filament
lead
A
110 v. D.C.
MAGNET
Collector
Deflecting
plate
E.S.
V.
1000 v. D.C.
Retarding
grid
E.S.
V.
Electrometer
E

FIGURE 3.

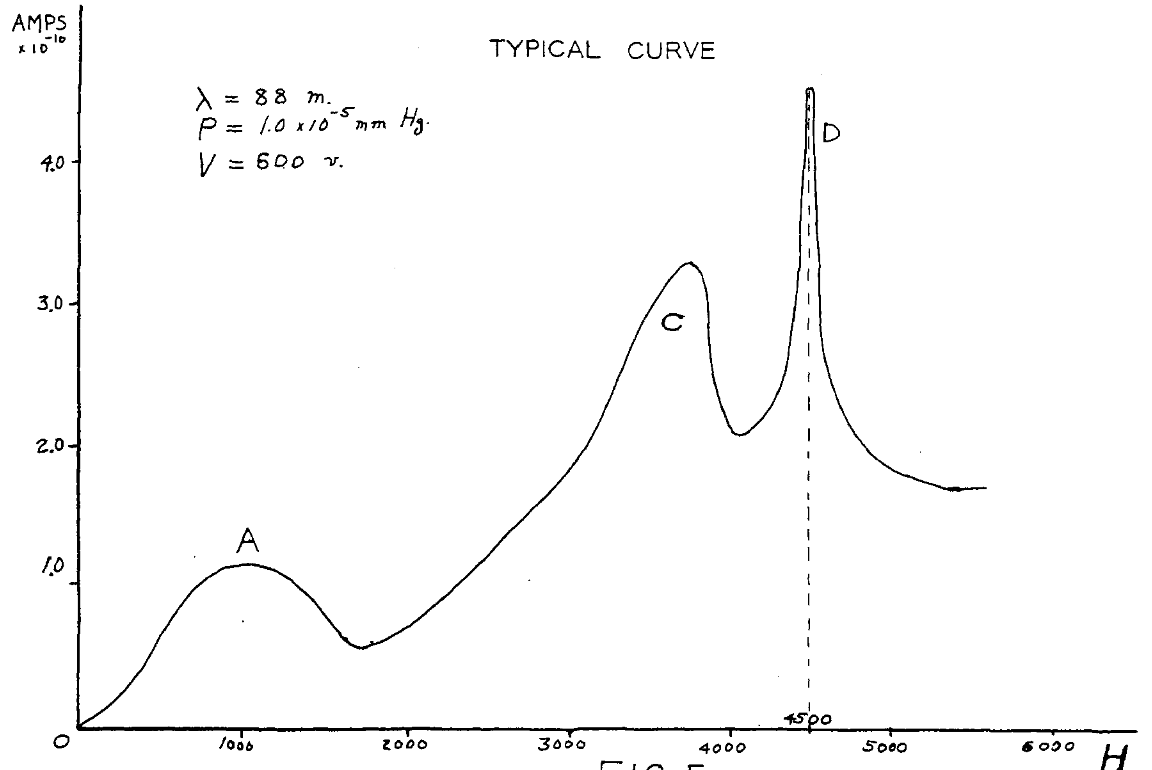
AMPS
x 10^-10
TYPICAL CURVE
λ = 88 m.
P = 1.0 x 10^-5 mm Hg.
V = 600 v.
4.0
3.0
2.0
1.0
0
A
C
D
4500
1000
2000
3000
4000
5000
6000
H

FIG. 5

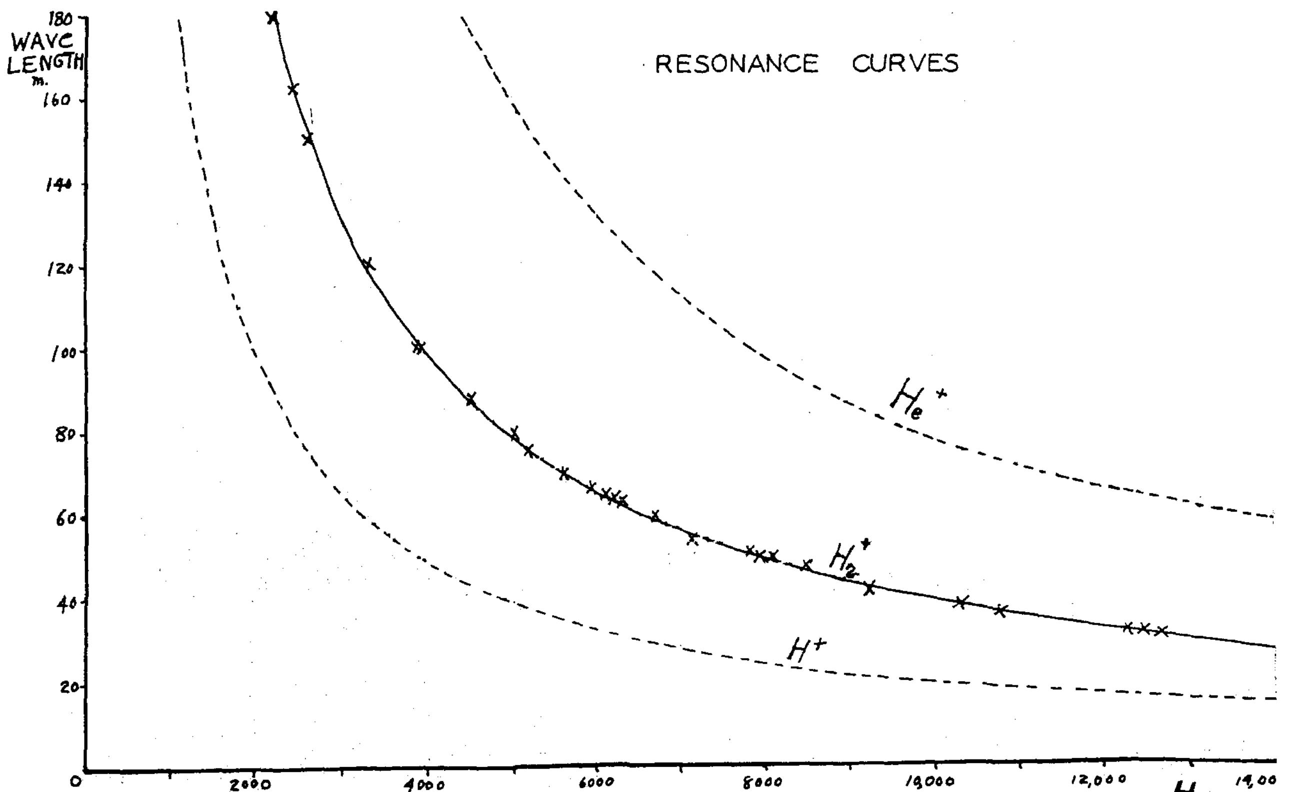
180
WAVE LENGTH
m.
160
140
120
100
80
60
40
20
0
RESONANCE CURVES
He+
H2+
H+
2000
4000
6000
8000
10,000
12,000
14,00
H

FIG. 6

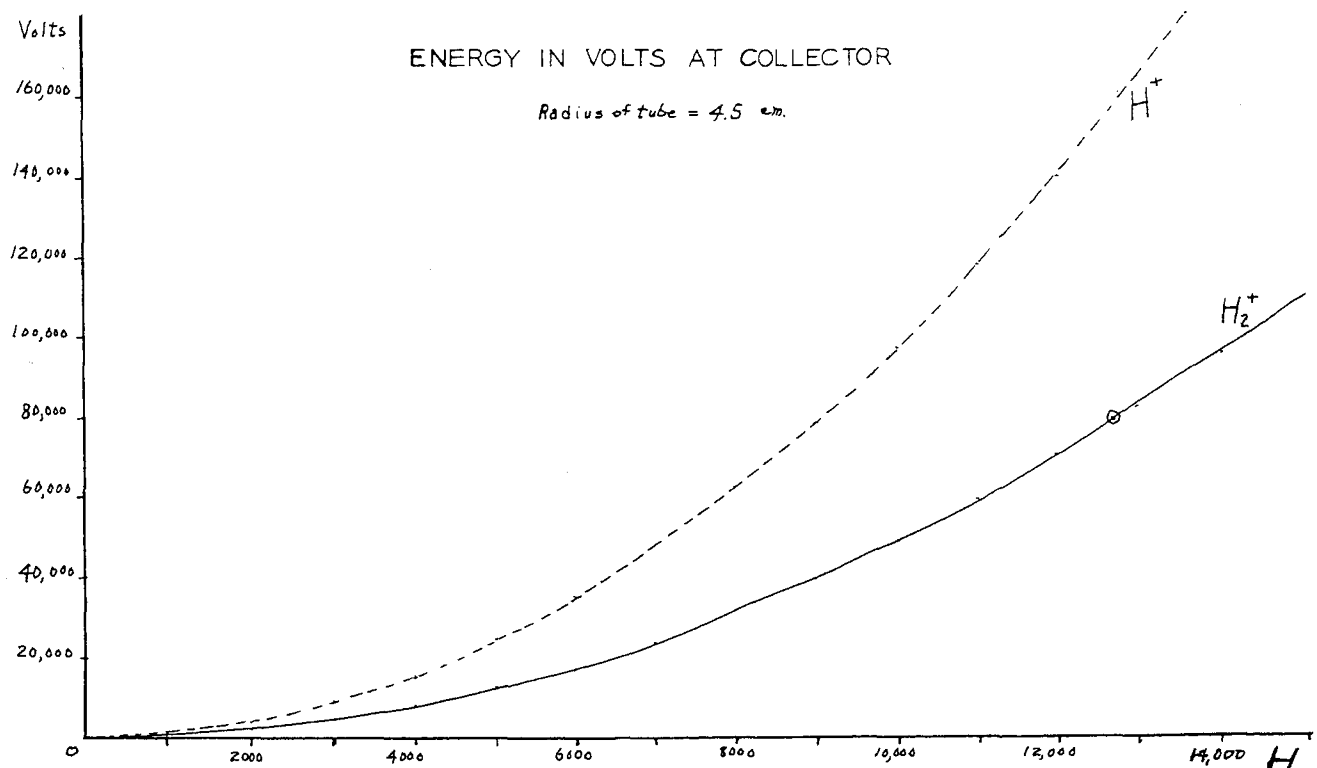
ENERGY IN VOLTS AT COLLECTOR
Radius of tube = 4.5 cm.
Volts
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
2000
4000
6600
8000
10,000
12,000
14,000
H
H^+
H_2^+

FIG. 7

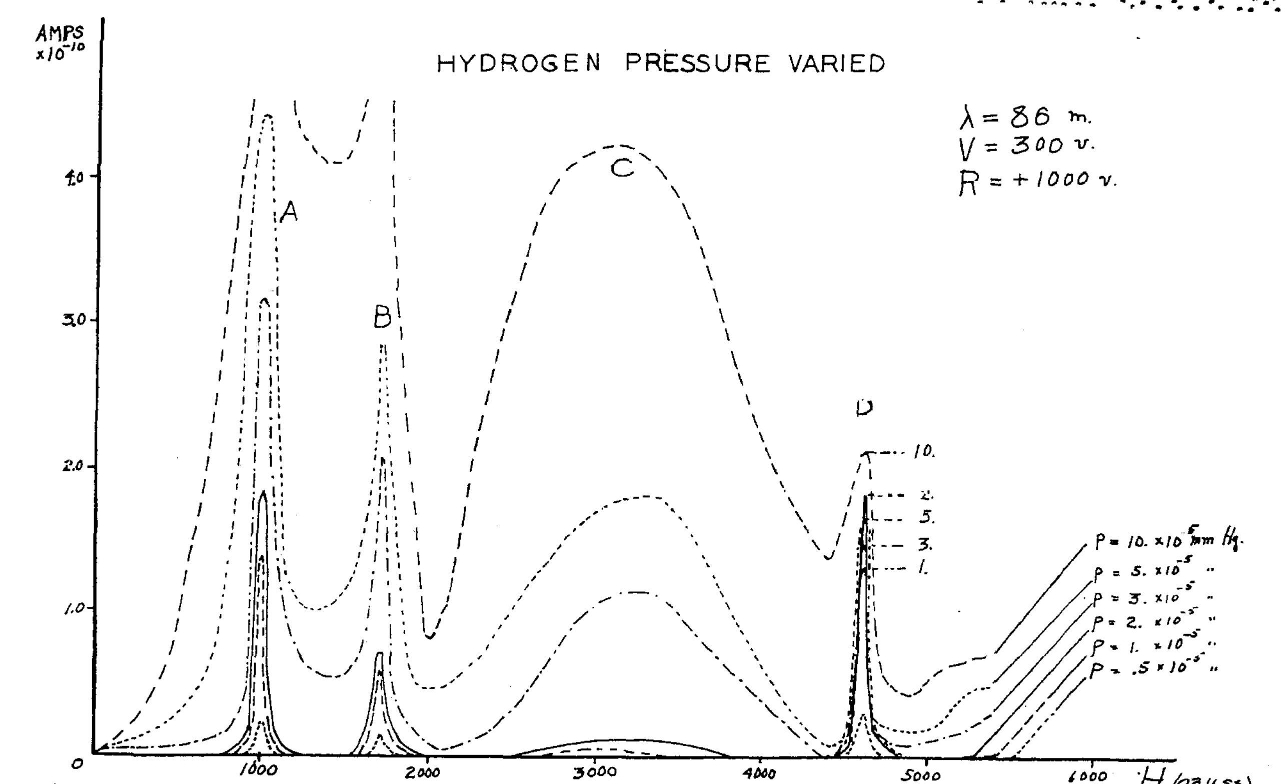
HYDROGEN PRESSURE VARIED
AMPS $\times 10^{-10}$
λ = 86 m.
V = 300 v.
R = +1000 v.
A
B
C
D
10.
2.
5.
3.
1.
P = 10. ×10⁻⁵ mm Hg.
P = 5. ×10⁻⁵ "
P = 3. ×10⁻⁵ "
P = 2. ×10⁻⁵ "
P = 1. ×10⁻⁵ "
P = .5 ×10⁻⁵ "
4.0
3.0
2.0
1.0
0
1000
2000
3000
4000
5000
6000
H (gauss)

FIG. 8

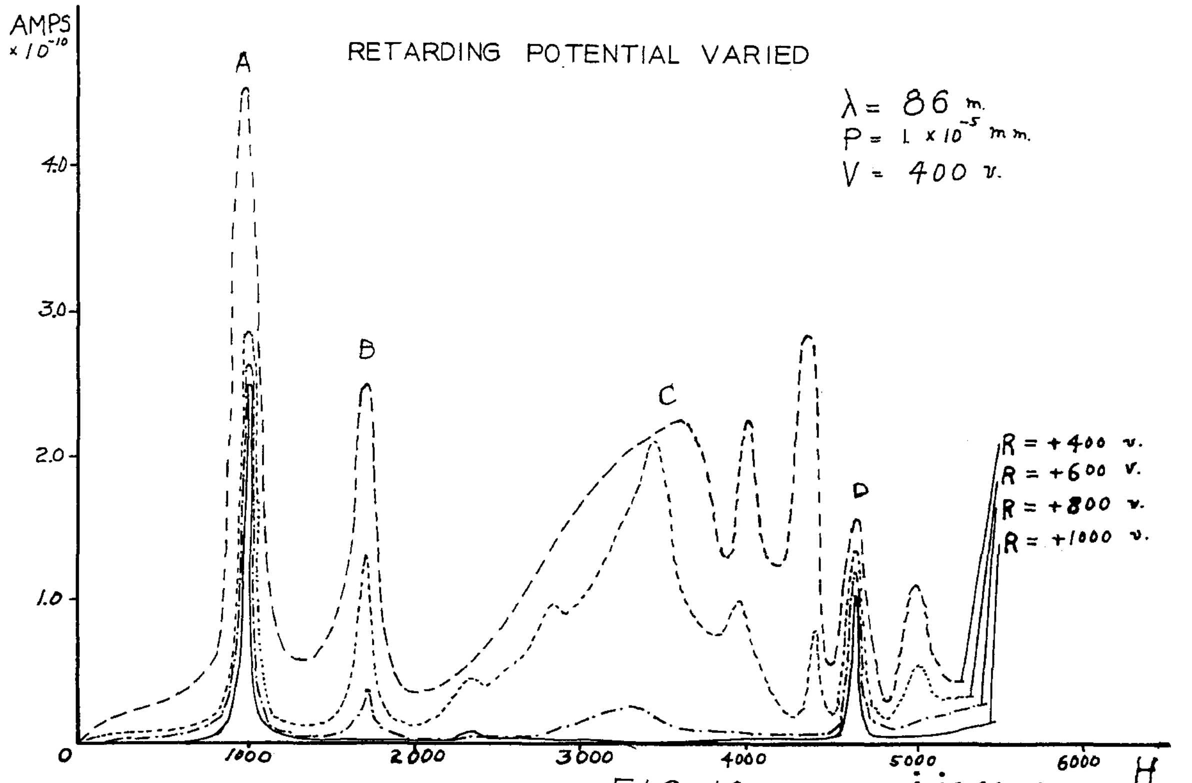
AMPS × 10^-10
RETARDING POTENTIAL VARIED
λ = 86 m.
P = 1 × 10^-5 mm.
V = 400 v.
A
B
C
D
R = +400 v.
R = +600 v.
R = +800 v.
R = +1000 v.
4.0
3.0
2.0
1.0
0
1000
2000
3000
4000
5000
6000
H

FIG. 10

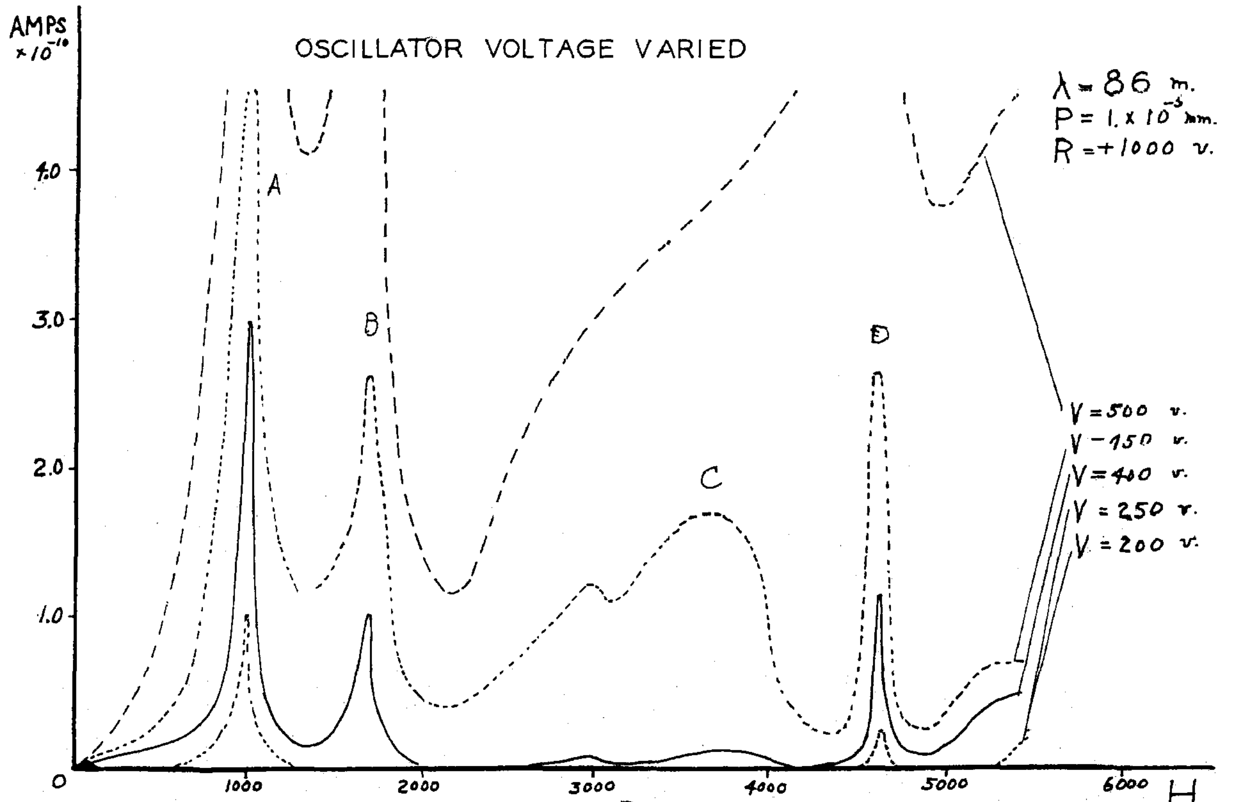
AMPS × 10^-10
OSCILLATOR VOLTAGE VARIED
λ = 86 m.
P = 1. × 10^-5 mm.
R = +1000 v.
A
B
C
D
V = 500 v.
V = 450 v.
V = 400 v.
V = 250 v.
V = 200 v.
4.0
3.0
2.0
1.0
0
1000
2000
3000
4000
5000
6000
H

FIG. 9

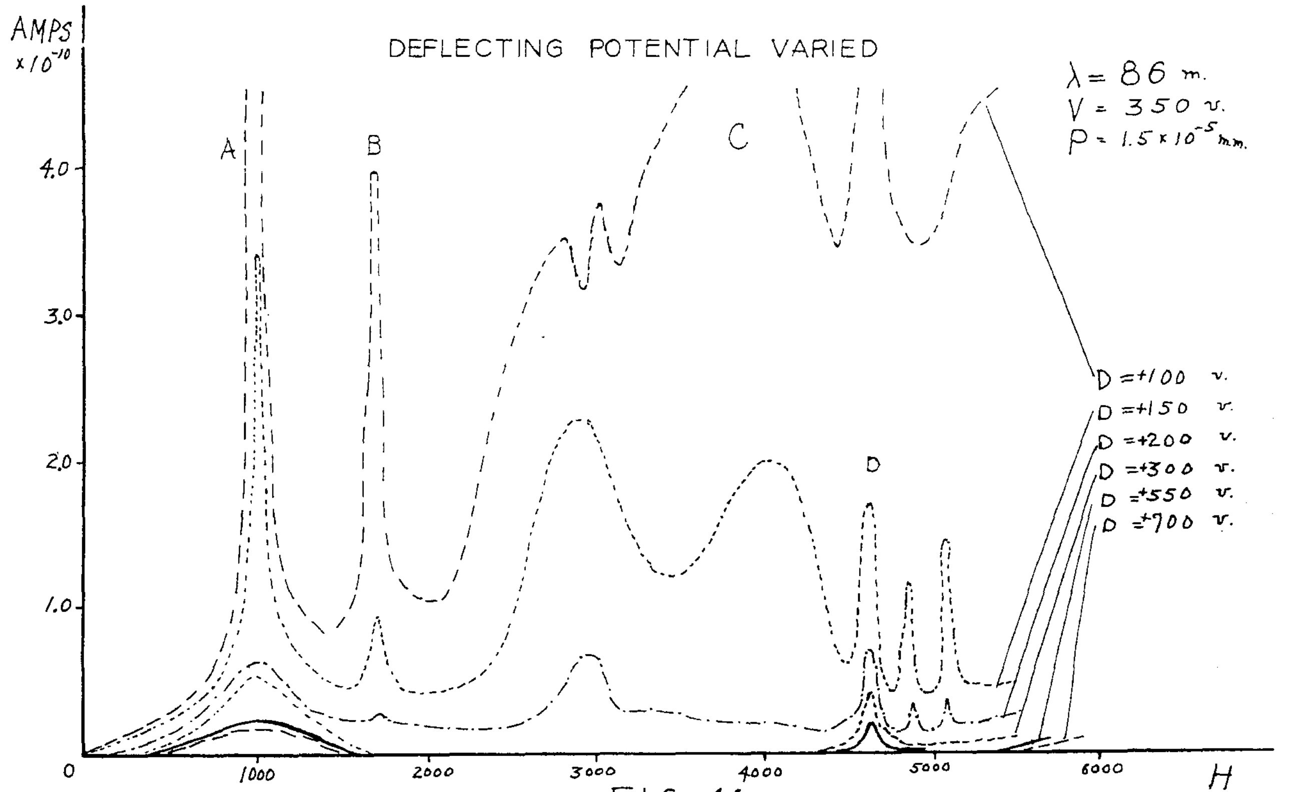
AMPS $\times 10^{-10}$
DEFLECTING POTENTIAL VARIED
$\lambda = 86$ m.
$V = 350$ v.
$P = 1.5 \times 10^{-5}$ mm.
A
B
C
D
D = +100 v.
D = +150 v.
D = +200 v.
D = +300 v.
D = +550 v.
D = +700 v.
4.0
3.0
2.0
1.0
0
1000
2000
3000
4000
5000
6000
H

FIG. 11

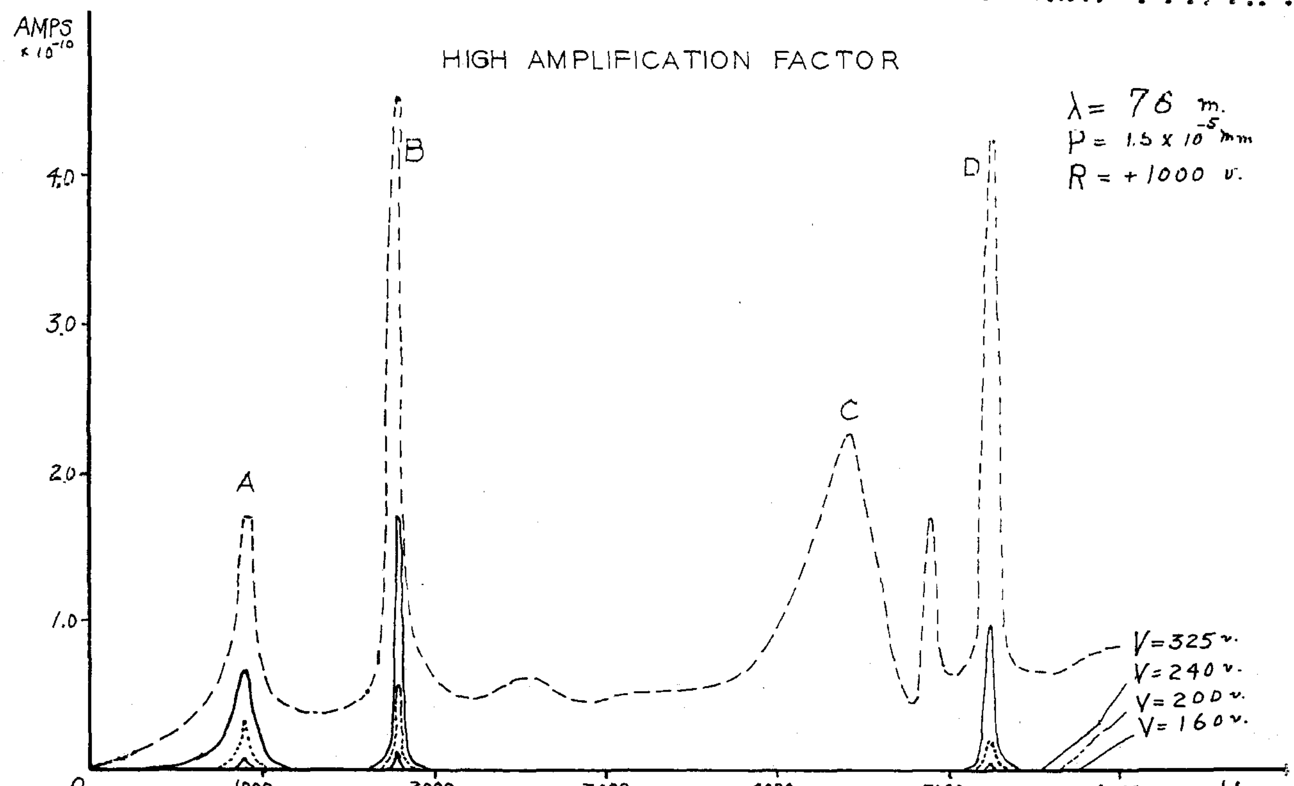
AMPS $\times 10^{-10}$
HIGH AMPLIFICATION FACTOR
$\lambda = 76$ m.
$P = 1.5 \times 10^{-5}$ mm
R = + 1000 v.
A
B
C
D
V=325 v.
V=240 v.
V=200 v.
V=160 v.
4.0
3.0
2.0
1.0
0
1000
2000
3000
4000
5000
6000
H

FIG. 12