The Multiple Acceleration of Ions to Very High Speeds

Ernest O. Lawrence and M. Stanley Livingston, *Radiation Laboratory, Department of Physics, University of California*

(Received March 12, 1934)

A larger model of our apparatus for the multiple acceleration of light ions, described in this journal about two years ago, has been constructed and has been in use in nuclear investigations during the past year. The larger equipment here described is capable of generating hydrogen ions with energies up to 5,000,000 volt electrons. At 3,000,000 volts, ion currents of $\frac{1}{3}$ microampere are readily obtainable and it is probable that water-cooling of the accelerators and the bombarded targets will result in considerably larger utilizable currents. The apparatus performs in a reliable manner and has many advantages for nuclear research. It is particularly fortunate that within the apparatus there are no high voltages which give rise to penetrating x-rays that interfere with observations of radiations emitted from targets bombarded by the high speed ions. The construction of an even larger apparatus, designed for the generation of hydrogen ions of about 10,000,000 volt electrons energy, has been undertaken.

Introduction

About two years ago we[1] described in this journal an apparatus designed especially for nuclear investigations, that generates high speed ions by repeated accelerations. The apparatus produced satisfactorily 1,200,000 volt protons and we were encouraged in the belief that much higher voltages could be reached in this way. Meanwhile we have constructed a larger model which has proved to be capable of accelerating hydrogen ions to voltages as high as five million. It has been used almost continuously during the past six months in certain preliminary investigations of nuclear phenomena in the range up to three million volts.[2, 3, 4, 5, 6, 7, 8] More precise experimental studies are in progress and it seems worth while at this time to present a description of the enlarged apparatus.

Apparatus

The present apparatus is fundamentally similar to the earlier model.[9] As before, ions formed near the center of the diametrical region between semi-circular hollow accelerating electrodes, spiral around on ever widening semi-circles from within one electrode to within the other, under the combined influence of a high frequency oscillating field between the electrodes and a uniform magnetic field normal to the plane of the electrodes. By suitable adjustment of the magnetic field and of the frequency of the oscillations, the ions are caused to circulate around in synchronism with the oscillating field, gaining increments of energy each time they cross the diametrical region. Finally, the ions emerge at the periphery of the apparatus, with an energy approximately equal to the voltage on the electrodes multiplied by the number of times they have crossed from one accelerator to the other in the course of their spiral paths. The magnetic field and final radius of curvature of the ions determine precisely their energy. We estimate from the geometry of the slit system that the

[1] E. O. Lawrence and M. S. Livingston, Phys. Rev. **40**, 19 (1932).

[2] E. O. Lawrence, M. S. Livingston and M. G. White, Phys. Rev. **42**, 150 (1932).

[3] M. G. White and E. O. Lawrence, Phys. Rev. **43**, 304 (1933).

[4] G. N. Lewis, M. S. Livingston and E. O. Lawrence, Phys. Rev. **44**, 55 (1933).

[5] E. O. Lawrence, M. S. Livingston and G. N. Lewis, Phys. Rev. **44**, 56 (1933).

[6] M. S. Livingston, M. C. Henderson, E. O. Lawrence, Phys. Rev. **44**, 781 (1933).

[7] M. S. Livingston, M. C. Henderson, E. O. Lawrence, Phys. Rev. **44**, 782 (1933).

[8] E. O. Lawrence and M. S. Livingston, Phys. Rev. **45**, 220 (1934).

[9] In this description it is assumed for the sake of economy of space that the reader has read the earlier paper (reference 1).

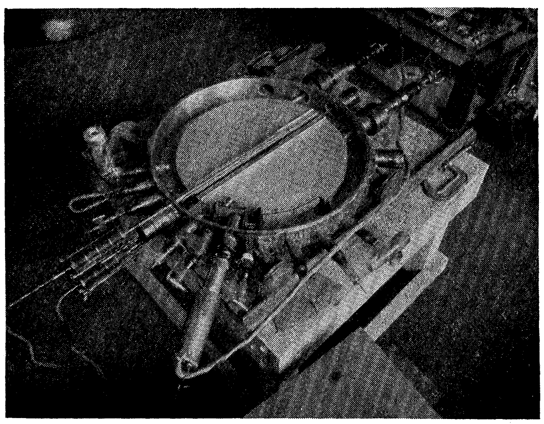

FIG. 1. Vacuum chamber with cover removed.

high velocity ion beam is homogeneous to at least five percent.

The vacuum chamber with cover removed is shown in Fig. 1. The bottom and cover of the chamber are circular plates of soft iron, $27\frac{1}{2}''$ in diameter and $1\frac{1}{2}''$ thick. The bottom is soldered to the bronze wall of the chamber, while the cover fits into a groove of the chamber wall and is rendered air-tight by sealing with beeswax and rosin. The inside separation of the plates is $3\frac{1}{2}''$. The vacuum chamber is placed between the poles of the large magnet so that the top and bottom of the chamber serve as the pole faces of the magnet. Actually, there is a space of $\frac{1}{4}''$ between the cover of the vacuum chamber and the top pole of the magnet, which is used for the insertion of pieces of iron to correct the inhomogeneity of the magnetic field produced by the magnet. This correction can be accomplished by adjusting in this gap thin pieces of iron of various shapes, while watching the effect on the intensity of the ion beam. There are numerous brass tubes soldered into the wall of the chamber, through which are mounted by means of glass and wax connections the various electrodes and adjustment devices.

In the former apparatus the high frequency voltage was applied to one semi-circular accelerator, the other accelerator being essentially the walls of half of the vacuum chamber. In the present design there are two semi-circular hollow electrodes mounted on insulating supports to which the high frequency voltage is applied, so that the difference of potential between the electrodes is twice the difference in potential between each electrode and the walls of the chamber. In this way the capacity of the oscillating system is made as small as possible. The electrodes are $20''$ in diameter and $1\frac{1}{8}''$ thick, leaving a distance between the electrodes and the top and bottom of the chamber of $1\frac{3}{16}''$. The capacity of this system is such that it is possible to apply oscillations of wave-length as low as 20 meters.

The accelerators, made of aluminum for lightness, are held in position by two supports. The main support is a water-cooled copper tube which, screwed into each accelerator, connects with the outside of the vacuum chamber through copper-to-Pyrex seals, which provide the necessary insulation. The other ends of the accelerators are supported by quartz rods which are adjustable from the outside. The orientation of the plane of the accelerating electrodes with respect to the magnetic field and with respect to each other is very important in the adjustment of the apparatus for best performance. The positions of the electrodes must be correct to a few tenths of a millimeter. This adjustment is readily accomplished by moving the quartz rods while the apparatus is in operation.

The high frequency power for the oscillating system is provided by a Federal Telegraph 20 kilowatt power tube, which is operated in a "tuned-grid-tuned-plate" circuit, and which is connected to an inductance with a step-up turns ratio of two or three. This inductance, in the form of a water-cooled copper coil mounted across the terminals of the accelerator electrodes, is readily adjustable for altering the frequency of the oscillations. In ordinary operation the high frequency voltage applied to the accelerators is about 20,000 with a power consumption of about 3 kilowatts.

In the present apparatus we are using essentially the same type of ion source as formerly. Spiral filaments are mounted near the center on insulating supports above and below the central region between the accelerators. Electron emission from the filaments passes along the magnetic lines of force between the accelerating electrodes, ionizing the gas (usually hydrogen) filling the whole vacuum chamber at a pressure of between 10^{-4} and 10^{-5} mm of mercury. In order to increase the obtainable ion currents, the filaments have been partially surrounded with water-cooled jackets, so that large currents of electron emission can be drawn without undue heating and evolution of gas in the chamber. The filaments of 12 mil. tungsten are wound in flat spirals of about $\frac{1}{4}''$ diameter. This design has proved satisfactory in avoiding distortion in the magnetic field. The electron emission from the upper filament strikes the water-cooled jacket of the lower filament, while the emission from the latter strikes the water-cooled jacket of the former.

Most of the ions that arrive at the periphery and that reach the collector start from a relatively small region between the accelerating electrodes. This proves to be, as expected, at a distance from the geometrical center about equal to the calculated radius of the first semi-circle described by the ions in the magnetic field. In order that the stream of electrons form ions at this optimum place, a sylphon arrangement is provided which makes it possible to move the filaments back and forth along the diametrical region, while the apparatus is in operation.

Fig. 2 shows diagrammatically the arrangement for withdrawing the ions from their circular paths within the accelerating electrodes. The ions emerge at the periphery of one of the accelerators through a slit and are caused to travel on a larger radius of curvature, by application of an electrostatic field between the accelerator and deflecting plates A and B. On emerging from the region between the deflecting plates the ions travel through slits C and D and enter the Faraday collector F. Various mica and metal foils are mounted on a wheel directly in front of the slit of the Faraday collector so

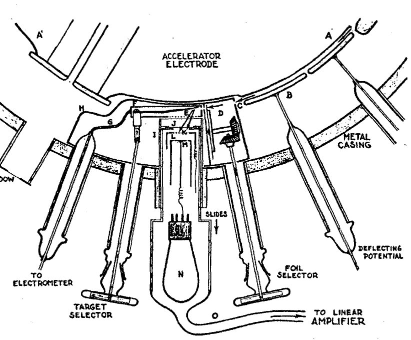

FIG. 2.

arranged that by turning a stopcock from the outside (labelled foil selector) various foils can be placed in the beam directly in front of the collector. In this way the speeds with which the ions strike the target E within the collector can be quickly reduced by various amounts. This arrangement has been found to be much more convenient than varying their speeds by changing the magnetic field and corresponding frequency of the oscillations.

Inside the Faraday collector is mounted a wheel,[10] which also can be turned from the outside by a ground joint arrangement (labelled target selector). On the wheel are mounted twelve different substances which can be turned in rapid succession into the beam at E. Radiations given off from the bombarded substances pass through a thin mica window (of about 1 cm air equivalent absorption) into an adjacent ionization chamber, JLM, where the resulting ionization is measured by a linear amplifier. A full description of this part of the apparatus will be submitted for publication by Dr. M. C. Henderson.

The general features of the electromagnet are shown in Fig. 3. It is of the double yoke design, with the exciting coils on each side of the gap. The magnet was constructed from the magnetic circuit of a Federal Telegraph 1000 kilowatt arc converter, designed by Dr. L. F. Fuller.[11] In adapting this arc converter magnet to our uses, it was necessary to change the position of the gap so that the exciting coils could be placed on both sides. Although the iron core has an effective diameter of 45 inches, in the present arrangement the pole face diameter is $27\frac{1}{2}$ inches. The total weight of the magnetic circuit, consisting of seven sections of cast steel, is about 65 tons. The exciting coils consist of eighteen flat coils of $1\frac{1}{4}$ by $\frac{1}{16}$ inch copper strip. There are nine coils in each tank and 200 turns in each coil, making a total of 3600 turns and about nine tons of copper in all. The coils are immersed in transformer oil and it is intended eventually, when large exciting currents are used, to install a circulating system to cool the oil. In the present

[10] The diagram shows the arrangement of some months ago wherein only four targets were mounted on a section of a circular disk.

[11] L. F. Fuller, Proc. Inst. Rad. Eng. 7, 449 (1919).

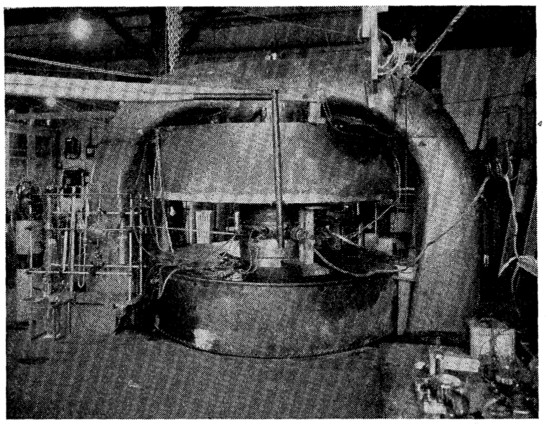

FIG. 3. General view of apparatus used in nuclear investigations.

experiments, however, the power requirements are so small that the heat capacity of the windings is quite adequate.

The general assembly of the apparatus as used in our recent preliminary nuclear investigations may be seen in Fig. 3. The vacuum chamber is shown between the poles of the magnet, with the ionization chamber, used to detect radiations from the target, in position. The first vacuum tube of the linear amplifier, which is close to the ionization chamber and consequently in a fairly strong magnetic field, is surrounded by an iron shield. From this tube a copper shielded cable extends to a table (lower right-hand corner) on which is placed the rest of the linear amplifier, a cathode-ray oscillograph, and a thyratron counting mechanism.

To maintain a good vacuum in the rather large metal chamber, it is necessary to use a fairly fast pumping system. A diffusion pump using Apiezon B oil, having a speed of 80 liters per second, is connected directly to the vacuum chamber by a brass tube four inches in diameter and four feet long. Although a vapor trap is not needed in the vacuum line, since the vapor pressure at room temperature of the pump oil is about 10^{-7} mm Hg, it is found convenient to have a liquid air-cooled surface in the vacuum chamber to condense vapors (such as carbon dioxide) given off from the metal in the early stages of operation. We have found that after the tube has been evacuated for several days, it is not necessary to use liquid air at all, and that indeed the pressure within the vacuum chamber as recorded by an ionization gauge (when the hydrogen flow is cut off) is often less than 10^{-6} mm Hg.

Alongside the magnet on the left is seen an arrangement for feeding hydrogen at a constant rate into the vacuum chamber. Since the vacuum pump and the oscillator, are on the other side of the magnet, they cannot be seen in the picture.

PERFORMANCE

With regard to the performance of the apparatus there are two major considerations: the highest speeds to which the ions can practicably be accelerated and the maximum intensities that can be produced. In both respects the performance of the present apparatus has been quite satisfactory.

Hydrogen molecule ions having energies of five million volt electrons have been produced. This voltage limit was established by the difficulty in correcting the inhomogeneity of the magnetic field produced by the magnet when fields of more than 18,000 gauss were used. No doubt this difficulty can be overcome and the present apparatus can be modified to generate about six million volt ions. However, to go to higher voltages it seems more desirable to build a larger apparatus, in which is used the full available diameter of the magnet pole faces, i.e., 45 inches. Such a larger apparatus, the construction of which we are now commencing, should produce hydrogen molecule ions and deutons with energies of about ten million volts or more.

We have been particularly pleased with the obtainable intensities of the high speed ion beams. For example, by using fifty milliamperes electron emission from the filament at the center of the tube, one-third of a microampere of three million volt hydrogen molecule ions is obtained. An unrectified alternating voltage is applied to the anode of the oscillator, and on account of this fact high frequency oscillations are effective in accelerating ions to the periphery only about ten percent of the time. In other words, when a current of 0.35 microampere of high speed ions is measured, actually the beam consists of about 3.5 microamperes of pulsating current, flowing about one-tenth of the time. This yield of high speed ions indicates that the focussing action of the curved electric and magnetic fields is so effective that practically all ions starting at the center of the tube arrive at the periphery. We are installing a six phase rectifier to supply an approximately d.c. voltage to the anode of the oscillator, and in this way the beam should be on nearly all of the time. Thus, we expect that the addition of the rectifier will increase the useful output of high speed ions to several microamperes. We intend also to increase the electron emission from the filaments at the center of the tube by a factor of ten. This should further increase the output of high speed ions in like proportion. It seems to us now that the practical limit of intensity of the high speed ion beam is set by the extent to which various parts of the apparatus, including the bombarded targets, can be sufficiently cooled. It is important to keep the metal parts cool in order to prevent undue evolution of gas. We are planning to water-cool both the accelerator electrodes and the targets.

When the apparatus is adjusted to accelerate hydrogen molecule ions, it accelerates with equal facility deutons which have the same e/m. Fortunately deutons have very long free paths in an atmosphere of deuterium, so that the pressure of deuterium in the vacuum chamber may be maintained at a surprisingly high value, about 10^{-4} mm Hg. The higher allowable working pressure, however, only partially offsets the smaller probability that an electron will ionize a deuterium molecule to form a deuton. The net result is that the deuton beams have an intensity of only about one-third that of the obtainable hydrogen molecule ion beams.

As regards the very important practical matters of reliability and ease of operation and adjustment, the apparatus functions in a most gratifying fashion. When a regulator was installed to keep the magnetic field constant, it was found that the high speed ion beam arriving at the target could be maintained surprisingly constant in intensity. In our preliminary nuclear investigations we have been impressed with the particularly fortunate circumstance that there are no high voltages in the vacuum chamber that give rise to penetrating x-rays, so that ionization chambers, Geiger counters, and other devices for detecting radiations, can be used close to the bombarded target without the interference of such spurious radiations.

We are greatly indebted to many people for their interest and support. The Federal Telegraph Company, through the interest of Dr. L. F. Fuller,[12] Vice-President, donated the steel castings of the magnet. The Research Corporation and the Chemical Foundation provided funds for the construction and installation of the magnet and accessory apparatus. The University Research Board with the approval of the President granted funds for operating expenses. We wish especially to thank Professor A. O. Leuschner, Chairman of the Board of Research, Mr. Howard A. Poillon and Dr. F. G. Cottrell of the Research Corporation, Mr. William W. Buffum of the Chemical Foundation, Professor L. F. Fuller and Professor R. T. Birge. We acknowledge with pleasure also the assistance throughout our experiments of Commander T. Lucci and the association of Dr. M. C. Henderson in the later work.

[12] Now Professor of Electrical Engineering, University of California.

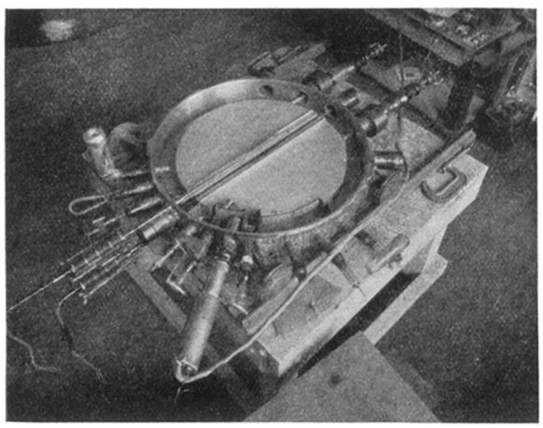

FIG. 1. Vacuum chamber with cover removed.

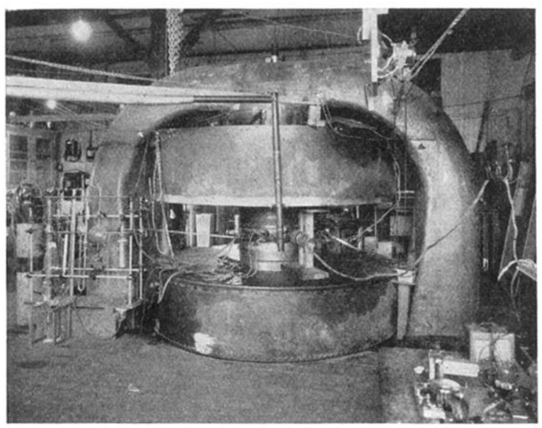

FIG. 3. General view of apparatus used in nuclear investigations.