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How to Make an Electrostatic Machine to Accelerate Both Electrons and Protons

by C. L. Stong
January, 1959

THE PARTICLE ACCELERATOR HAS about the same relationship to nuclear physics that the telescope has to astronomy. The accelerator probes the microcosm; the telescope, the macrocosm. Like the telescope, the accelerator can open exciting vistas to the amateur. But unlike the telescope, the accelerator has failed to attract a large amateur following. The notion seems to have got around that a small particle accelerator is little more than a toy. But in 1932 the British physicists J. D. Cockcroft and E. T. S. Walton did important pioneer work in nuclear physics with a 150,000-volt accelerator of the electrostatic type which today can be built for less than $200. With it Cockcroft and Walton succeeded in transmuting lithium into unstable beryllium, which then broke down into helium with the release of energy on the order of 17 million electron volts-scarcely the performance of a toy. A beam of particles from a machine of this size is capable of cutting the time of chemical reactions, of inducing mutations in living organisms, of altering the physical properties of organic compounds and of producing scores of other interesting effects.

F. B. Lee, a chemical engineer and faculty member of the Erie County Technical Institute in Buffalo, N. Y., has designed an electrostatic accelerator suitable for amateur construction which is similar to the Cockcroft-Walton machine but has more than twice its power. "Unlike the accelerator preferred by the physicist," writes Lee, "this one is designed for the amateur chemist. The beam of electrons it produces is brought out of the accelerator to irradiate targets in the open air. The physicist usually requires a closely collimated beam in which all particles have about the same energy, whereas the chemist is satisfied with a more diffuse beam in which the energy of the particles varies considerably. Since the targets irradiated by the chemist are usually rather thick, it is almost impossible to provide all sections of the irradiated material with electrons of uniform energy even if this were desirable. Fortunately it is usually satisfactory to have a large percentage of the electrons penetrate the target completely. The ions produced within the target by the beam are largely independent of the energy of the beam, but the permissible thickness of the target increases with the accelerating voltage. Electrons accelerated to an energy of 250,000 volts will penetrate metallic aluminum to a depth of about .25 millimeter; polyethylene, to a depth of some three millimeters; air, to a depth of some two meters. The depth of penetration is roughly inversely proportional to the density of the target material and to the square of its atomic weight.

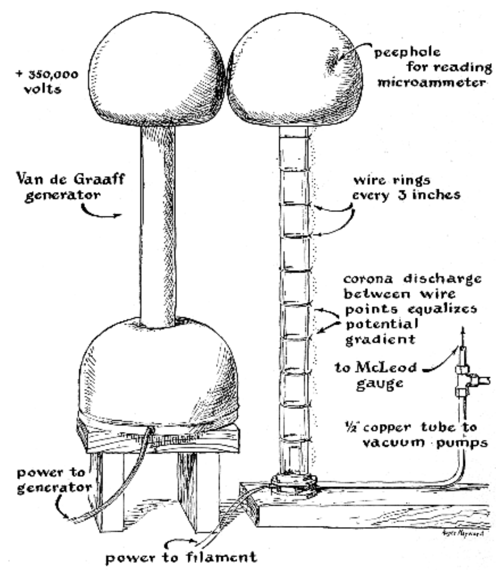

Figure 1: An electrostatic particle accelerator with a Van de Graaff generator as its power supply

"With the machine I shall describe amateurs can perform endless experiments based on the ionization of target materials by electrons. In the case of hydrocarbon targets numerous hydrogen atoms are dislodged from their sites in the molecule by the stream of fast-moving charged particles. Some of the atoms promptly combine into molecules of hydrogen (H_2) and escape as gas. Pairs of carbon atoms so stripped can then combine to cross-link the hydrocarbon molecules. Such cross-linking has a profound effect on the physical properties of the irradiated substance. For example, when molecules of the plastic polyethylene are cross-linked by irradiation, the plastic becomes much harder and melts at a higher temperature. The field is new and full of opportunities for the amateur who enjoys original work.

"The electrostatic accelerator may be thought of as a highly developed two-element electronic tube. It consists of an evacuated tube fitted with a source of electrons or protons at one end, an accelerating electrode at the other end, and a high-potential electric field between the two. If the accelerating electrode is made positive and the source is either a filament, a radioactive or photoelectric surface, or even a sharp point of metal, the resulting beam will be composed of electrons. If the accelerating electrode is made negative and a tiny amount of hydrogen is admitted to the tube, the gas will ionize and the beam will consist of hydrogen nuclei (protons).

"The major requirements for constructing a linear accelerator are a source of high potential and a vacuum system capable of reducing atmospheric pressure (760 millimeters of mercury in a mercury manometer) down to .00001 mm. of mercury. The high potential may be generated by a Van de Graaff machine such as the one described in 'The Amateur Scientist' for May, 1957. A machine capable of delivering 20 millionths of an ampere (20 microamperes) at a potential of 500,000 volts can be built for less than $30.

"The tube for my accelerator was constructed from a junked piece of Pyrex pipe two inches in diameter and about three feet long. A 24-inch length would' have been preferable, but the dimensions are not critical. A hardwood plank eight inches wide, two inches thick and five feet long serves as a common base for the accelerator and vacuum pumps. The accelerator tube is mounted vertically near one end of the base, as shown in the accompanying drawing [*Figure 2*]. The cathode fitting, which closes the lower end of the tube, was machined from a piece of brass 2 1/2 inches in diameter and one inch thick. A hole is drilled in one wall to receive the half-inch copper pipe which connects the tube to the vacuum pumps. Another hole, in which an 1/8-inch pipe thread is cut, receives a standard quarter-inch compression fitting which serves as a gland for the filament assembly. The filament assembly is comprised of a quarter-inch rubber rod about half an inch long, through which two No. 18 enameled copper lead wires are run to support a half-inch length of No. 30 Nichrome wire. The lead wires were coated with vacuum grease before they were forced through the holes in the rod. The rod was then greased lightly and slid into the compression fitting, after which a collar of rubber tubing was slid over it. Finally the compression nut was run home to seal the assembly. Details of the gland are shown at upper left in the second illustration. The entire unit is vacuum-tight, easy to assemble and has given no trouble.

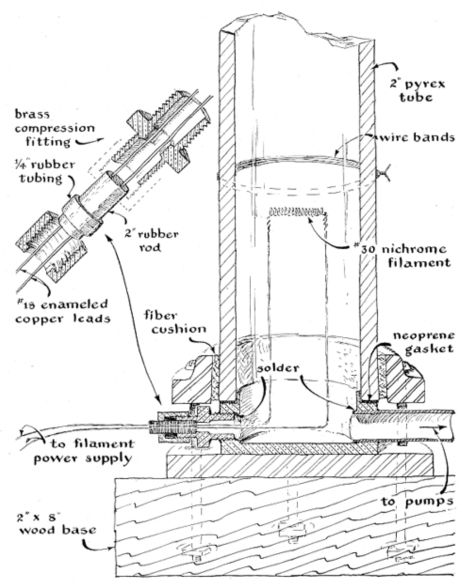

Figure 2: Details of the filament assembly for the accelerator

"With the Van de Graaff machine suggested, the tube develops a beam of only 10 to 20 microamperes, and the filament operates at a proportionately low temperature. The optimum filament temperature must be determined experimentally. The temperature is controlled by a rheostat in series with the power supply, which may be a simple doorbell transformer. When the temperature is too high, excessive emission lowers the resistance of the tube and consequently the voltage of the Van de Graaff machine. Lowered tube-voltage of course means lowered beam-energy. In contrast, low filament-temperature results in scanty filament-emission, which lowers the beam current and increases the tube resistance. Thus at low filament-temperature the tube develops maximum voltage, and proportionately higher energy is imparted to individual particles in the beam. This compensates somewhat for the lower beam-current. For this reason downward departures from the optimum value of the filament temperature are preferable to upward departures.

"The electron beam is restricted to the axis of the tube by a symmetrical electrostatic field established by a series of rings spaced at three-inch intervals along the tube. The rings consist of four turns of 26-gauge bare copper wire. The ends of the wire are twisted tightly enough to hold the coil in place on the glass and are spread about half an inch apart. The points so formed act as corona electrodes and pick up charge from the surrounding air until electrical equilibrium is established between the air and the rings. In larger tubes, fixed resistors are substituted for the corona points. This, however, is not necessary in machines operating at 500,000 volts or less.

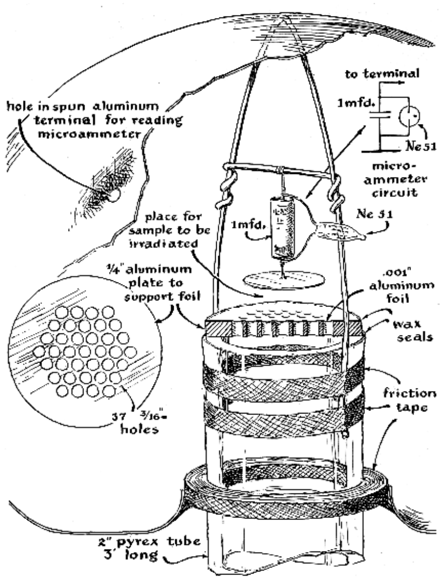

Figure 3: Details of the anode window and microammeter for the accelerator

"The upper end of the accelerator is closed by a window of aluminum foil through which the beam passes into the air. To prevent the foil from rupturing under atmospheric pressure, it is supported by an aluminum grid made of quarter-inch aluminum plate. The plate is drilled with 37 holes 3/16 of an inch in diameter and arranged in a hexagonal pattern [*see illustration in Figure 3*].

Approximately 50 per cent of the grid area is thus open. The grid is cemented to the upper end of the tube with vacuum wax. The foil window, which should not exceed .001 inch in thickness, is similarly cemented on top of the grid.

"High-vacuum equipment is sealed with special waxes which have a low vapor-pressure, *i.e.*, they evaporate so slowly that their vapors exert very little pressure. These include de Khotinsky wax, which has a vapor pressure of one micron of mercury; Dennison waxes, with a pressure of .01 micron; and Picein and Apiezon-W waxes, with a pressure of .00001 micron. The experimental physicist John Strong recommends a wax made by melting together equal parts of beeswax and rosin. The vapor pressure of this mixture approaches that of Picein and Apiezon-W. It is applied smoking hot with a medicine dropper, and though it adheres well to cold surfaces, it is good practice to warm the glass or metal parts on which it is spread. I used Picein which chanced to be available. The parts were heated to the softening point of the wax, after which the joints were rubbed with the wax until a thin coating adhered. The pipe and grid were then pressed together until the wax set. Next the side face of the grid was coated, and the foil was pressed in place. The seal was completed by applying a thin bead of wax around the outside edges of both joints.

"A loop of 12-gauge brass wire was then attached to the top of the tube by friction tape as a frame to support the 12-inch spherical terminal. A simple microammeter, which consists of a high-resistance capacitor of one microfarad bridged by a 1/25-watt neon tube, is also supported by the frame. The input terminal of the microammeter is a 1/2 inch disk of 12-gauge sheet aluminum supported by one axial lead of the capacitor at a height of 3/4 inch above the aluminum window. The remaining lead of the capacitor is soldered to a cross wire attached to the brass loop.

"The electron beam enters the disk and eventually charges the capacitor to the firing potential of the neon tube, which then flashes and discharges the capacitor. A current flow of one microampere causes the tube to flash at 15-second intervals, the flashing rate being proportional to the intensity of the beam current. A dimple roughly two inches wide and half an inch deep is made in the spherical terminal opposite the neon tube, and a quarter-inch peephole is drilled at the bottom of the depression. The dimple prevents the concentration of a strong electrostatic field at the sharp edge of the hole and the loss of current through corona discharge. The neon tube can be observed safely at a distance of about two feet. The positive terminal of a 350,000-volt Van de Graaff generator is placed in contact with the accelerator terminal as the source of accelerating potential. Samples of material to be irradiated, such as hydrocarbon compounds or seeds, are placed on a carrier of thin polyethylene sheet between the aluminum-foil window and the disk electrode of the microammeter.

"The accelerator tube must be evacuated to pressure on the order of .01 micron of mercury to prevent excessive collisions between the accelerated particles and molecules of gas. Molecules ionized by such collisions are accelerated toward the filament as positive ions, collide with other molecules and create still more ions until the resulting avalanche of charged particles paralyzes the tube. At a pressure of .01 micron, gas molecules have a mean free path of 15 feet or more, and collisions are accordingly infrequent.

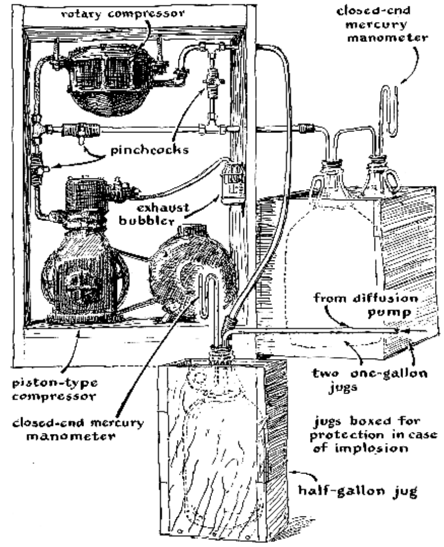

Figure 4: "Roughing" pump assembly for the vacuum system of the accelerator

"A vacuum of this quality requires elaborate pumping equipment and extreme care in eliminating leaks. The most inexpensive commercial equipment capable of attaining the desired pressure is priced at about $200; hence there is substantial inducement beyond the mere challenge of an interesting problem to use a home-built substitute-such as the compressor units from old refrigerators.

"A rough vacuum of 20 millimeters or so is easily pumped either by a water aspirator or a refrigerator compressor (connected backward). Higher vacuums may be attained by connecting two refrigerator compressors of the rotary type in series to make a two-stage unit. Compressors of the piston type are not satisfactory unless they are modified, because the inlet valve which is actuated by gas pressure stops working when the system has been pumped down to a pressure of about 30 millimeters.

"It is possible to make a 50-per-cent improvement in the performance of piston compressors by bypassing the inlet valves. Rotary compressors, such as are used in the Frigidaire, have no valves and are easily adapted to multistage use. My system uses two second-hand units, one of the piston type and the other of the rotary, as "roughing" pumps. These were purchased from a local dealer in used iceboxes for $5 each, including the motors. The intake valve of the piston unit was bypassed by drilling a hole in the side of the cylinder just above the low point of the piston's travel. A short length of copper tubing was brazed to this port as the new intake. The piston covers the port as it ascends, thus eliminating the need of gas pressure to actuate the inlet valve. The intake of this unit is connected by a hose to the discharge port of the rotary compressor. A system of pipes and valves permits the discharge from the rotary compressor to be connected either to the intake of the piston unit or to a two-gallon reservoir. A similar system of pipe-and valve-connections permits the intake of the rotary compressor to be. connected either to the outlet of a diffusion pump or to the reservoir. Connected in tandem and exhausted into the air, the pumps will reduce the pressure to about one millimeter. But by exhausting into the two-gallon reservoir (previously pumped to a pressure of one mm.) it is possible to obtain a final vacuum of about .1 mm.

"Special oils of low vapor-pressure must be used for lubrication. The pumps are first

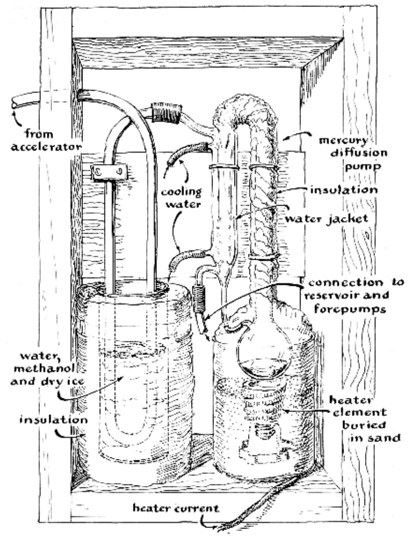

Figure 5: Mercury diffusion pump and cold trap for the vacuum system

drained of conventional oil, then filled with about half a pint of paraffin oil, operated for 10 minutes and drained. If the paraffin oil shows traces of the old oil, the pumps are again flushed with paraffin oil.

"They are now filled with vacuum oil. Some volatile fractions may still remain. These can be removed by several hours of operation. Unlike conventional vacuum pumps, refrigerator compressors have large areas of contact between the oil and gas on the discharge side of the pump and are accordingly susceptible to volatile fluids.

"My vacuum reservoir consists of a pair of one-gallon glass jugs connected with the pumps by half-inch copper pipe inserted through rubber stoppers coated with vacuum grease. The reservoir is first exhausted by the tandem pumps. The pinchcocks are operated to switch the reservoir to the output of the rotary compressor. If the system does not liberate too much gas, one pumping of the reservoir will last many hours.

"The final pressure at which the tube works is achieved by means of a diffusion pump. A half-gallon reservoir is connected between the inlet of the rotary pump and the exhaust of the diffusion pump. Pressure in both reservoirs is indicated by a manometer connected as shown [*see illustration in Figure 4*]. When the pressure of either reservoir rises above three millimeters, it is reconnected to the inlet of the rotary unit and pumped down to one mm.

"My attempt to make a mercury diffusion pump from spare pipe-fittings did not succeed. I must confess, however, that I did not try very hard. The project should not be difficult for those with access to machining facilities. Diffusion pumps of various designs and capacities are available on the market from $30 up. The small sizes require about three pounds of mercury, which costs about $12 more. A heating unit ranging from 100 to 300 watts must also be provided for vaporizing the mercury. My pump [*see illustration in Figure 5*] was made by a local glass-blower to operate against a back pressure of about four millimeters Judging by the literature, many commercial pumps require a back pressure of .3 mm. or less. In general, the rate at which diffusion pumps remove gas from the system varies inversely with the back pressure against which they operate. The ultimate pressure they produce depends on the vapor pressure of the pumping fluid, which includes various oils in addition to mercury. Vapor pressure, in the case of mercury pumps, establishes a lower limit of one micron (.001 millimeter) unless the system is equipped with a trap to prevent the mercury vapor from entering the evacuated vessel. A cold trap made by refrigerating part of the plumbing between the diffusion pump and the accelerator tube enables the pump to achieve a pressure of .01 micron if the temperature of the trap is maintained at minus 40 degrees centigrade. My trap consists of a U-shaped section in the half-inch copper line. The section is inserted in a tin can insulated by a half-inch layer of cardboard covered by aluminum foil. The cooling mixture consists of equal parts of water and wood alcohol to which crushed dry ice is added as required. The trap is not chilled until the system has been pumped to one or two microns. This procedure prevents the formation of ice in the trap which will subsequently release water vapor as low pressures are attained, and thus increase the pump-down time substantially.

"The mercury is vaporized by a unit from a radiant heater to which an extra winding was added to reduce its rating to 150 watts. The heater is mounted in a tin can and buried in sand up to the top of the ceramic cone. Heat radiated from the center of the cone is sufficient to energize the pump. A 150-watt incandescent lamp would doubtless work as well. In selecting a site for the apparatus keep in mind that most diffusion pumps require a supply of cooling water.

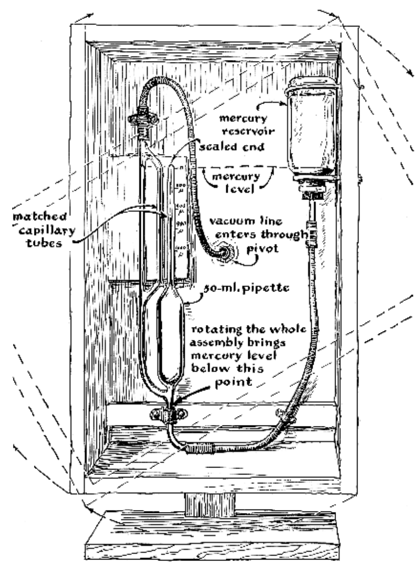

Figure 6: McLeod gauge for measuring low pressure in the vacuum system

"Once the vacuum system is complete, the easy part of the job is ended. One then locates and seals the leaks. This tedious procedure can consume days or weeks depending upon the experimenter's luck and the efficiency of his leak detection gear.

"At least three closed-end mercury manometers should be provided. These consist of quarter-inch glass tubes about 24 inches long. If soda-lime glass is used, one end can be sealed over a Bunsen burner. A short section six inches from the closed end is then heated to softness and bent 180 degrees so that it lies parallel to the long portion of the tube. The long portion is then heated at the point opposite the closed end and similarly bent 180 degrees. The result is a flat 'S' [*see illustration below*]. Enough mercury is introduced into the tubing to fill the closed leg of the 'S' and about 20 per cent of the center leg. This can be accomplished by placing the tube in a reclining position and rocking it as the mercury is introduced into the open end. The closed leg must be completely filled without a trace of bubbles. One manometer is inserted in each of the reservoirs and another is temporarily connected to the accelerator tube.

"The roughing pumps are now started. If the mercury has not separated from the closed end of the manometer at the end of 15 minutes, the tube may be tapped gently. If this does not cause separation, check the pumps for faulty operation. After the pressure has been reduced to about one millimeter, the individual elements of the system should be isolated by closing all pinchcocks. The pumps are then stopped. The manometers may be provided with cardboard scales calibrated in arbitrary units. Manometer readings are recorded at the end of the pump-down and compared with a second set of readings made after an interval of 12 to 24 hours. Each section of the system will doubtless show a rise in pressure. Vacuum grease is then applied to all joints where a leak is suspected and the procedure is repeated. Ultimately the system will appear to be tight. A run can then be attempted with the diffusion pump in operation. In my system a pressure of one micron is achieved at the end of about 30 minutes, and a usable vacuum in the accelerator tube is attained about eight hours later. The roughing pumps are used for about an hour or until the tube pressure drops to .5 millimeter, after which they are valved off and shut down. The half-gallon reservoir on the outlet of the diffusion pump has sufficient capacity to receive the exhaust for several days of continuous pumping.

"Most experimenters will want at least one high-vacuum gauge of the McLeod type to check leaks too slow to show on the manometers. The McLeod gauge operates on the principle of trapping gas in a chamber of substantial volume and then compressing it by a column of mercury into a closed capillary tube. The pressure of the compressed gas is then compared with that in the vacuum system by observing the difference in height to which a column of mercury rises in a matching capillary connected to the system. One of my gauges is shown in the accompanying illustration [*Figure 6*]. It was made of discarded laboratory pipettes that had broken tips but were otherwise usable. Readings made with it are accurate down to about 10 microns, but gas released from the rubber connections prevents measurements at lower pressures. A second gauge made by a professional glassblower detects .1-micron pressures. The instruments require about three pounds of mercury Dibutylphthalate ($1 per pound) has been substituted for mercury as an economy measure; I have also tried salad oil and olive oil. These are usable if they are boiled for a few minutes at one millimeter of pressure, but they absorb volatile materials easily and in time become erratic.

"Those who build this accelerator would be well advised to read the several reference texts listed in the bibliography before purchasing supplies.

"Several hazards should be noted. First, a large evacuated glass vessel can, if it breaks, scatter glass at high velocity over a large area. It is essential that the glass reservoirs be enclosed in wooden or metal containers. Second, keep in mind that the accelerator is a close relative of the X-ray tube. The penetrating power of X-rays is determined in part by the atomic weight of the target bombarded by electrons. X-radiation emitted by light elements such as aluminum is readily absorbed by glass, thin metal or even air. But heavy metals, such as copper, generate penetrating and dangerous radiation. It is important, therefore, to expose only materials of low atomic weight to the beam. Third, the inexperienced worker should observe care in handling mercury, particularly when it is confined in glass tubes. If air is admitted abruptly to a manometer of the closed-end type, it is astonishing what damage the 'water hammer' (in this case mercury hammer) can do. Enclose the manometers in transparent plastic bags. Just having a few pounds of mercury around constitutes a substantial hazard because the vapor pressure of mercury is high enough to worry about even at temperatures as low as 80 degrees Fahrenheit. Fourth, although the voltage of the Van de Graaff generator is not necessarily hazardous in itself, an unexpected shock can throw one off balance and thus lead to an accident.

"I will be glad to provide assistance in locating supplies. Letters addressed to F. B. Lee, Erie County Technical Institute, Buffalo, N. Y., will be answered as promptly as possible."

Bibliography

MODERN PHYSICAL LABORATORY PRACTICE. John Strong, with H. Victor Neher, Albert E. Whitford, C. Hawley Cartwright and Roger Hayward. Blackie and Son, Ltd., 1938.

VACUUM EQUIPMENT AND TECHNIQUES. Edited by A. Guthrie and R. K. Wakerling. McGraw-Hill Book Company, 1949.

Suppliers and Organizations

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4,228.5.

James H. Bly of the Eligh Voltage Engineering Corporation in Burlington,'" Mass., recommends a change in the design of the particle accelerator described in this department last January. "In general, I think it is fair to say that we like the design approach to this machine very much," Bly writes. "However, we are somewhat concerned over those portions of the article that are concerned with the hazards involved. We agree wholeheartedly with what was said concerning the hazards of glass breakage and the use of mercury. We feel strongly, however, that there is inadequate discussion of the potential hazards due to X-rays and electrons. Even though the experimenter restricts himself to targets of low atomic number, there will inevitably be some generation of high-energy X-rays when using electrons of 200 to 300 kilovolt energy. If currents as high as 20 microamperes are achieved, we are sure that the resultant hazard is far from negligible. In addition, there will be substantial quantities of scattered electrons some of which will inevitably pass through the observation peephole. Although it is conceivable that it would be safe to look through this peephole from a distance of two feet, we are very doubtful that this is in fact the case. We believe the article would have been improved considerably if these hazards had been more thoroughly explored."

The apparatus described has been in operation for a year and has been tested exhaustively for radiation hazard. The article might well have pointed out, however, that one invites trouble by remaining near particle accelerators when they are in operation, or even by staying in the same room with them during prolonged periods of operation. F. B. Lee, who designed the apparatus, does not share Bly's concern about the hazard of scattered electrons from the peephole. As a precaution, however, the peephole may be covered on the inside by a small piece of window glass which will plug the hole completely for electrons. As an alternative the neon tube can be cemented in the peephole and connected with its circuit through a pair of contacts (an arrangement that would permit the high-voltage terminal to be removed when desired). The lamp could then be observed at a distance with the machine in operation.

George Gaylord Simpson, curator of fossil mammals and birds at the American Museum of Natural History, calls our attention to a hazard of a different sort. He writes: "In your February issue 'The Amateur Scientist' urges more amateurs to collect fossils and assures them that 'on public lands U. S. citizens can gather as many as they want.' That

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Cost: $0-100 About These Ratings	Difficulty: ■■■□□	Danger 2: (Minor injury possible)	Utility:

Experiments Which Show That the Earth Functions As an Electrostatic Machine

by C. L. Stong
May, 1957

ONE SUNNY MORNING last fall a jolt of electricity knocked Fred Ellis, an Ohio radio ham, from the roof of his barn. Fortunately Ellis landed on a stack of straw and lived to tell the tale. "I started to hook a ground wire to a 50-foot antenna tower on the roof," he writes, "when a fat spark jumped from the metal tower to my hand and knocked me off balance. Although the weather was hot and dry there had been no breeze of any consequence for several days. Hence the charge could not have been generated by wind friction. How do you account for it?" In Minneapolis a steeplejack was badly burned earlier in the year when a similar spark jumped from the base of a flagpole and touched off a nearby pile of gasoline-soaked rags. Again the accident occurred on a clear, still day. A television viewer on a Pennsylvania farm, plagued for months by a strange electrical disturbance which occasionally obscured his picture, finally cured the difficulty when he detected small sparks jumping from the sheet metal cupola on his house. The trouble was ended by grounding the cupola. In all three cases the explanation has to do with the sometimes-overlooked fact that the earth is, among other things, the negative electrode of a huge electrical generator of the Van de Graaff type. Many details of this natural generator await explanation; if you enjoy electrostatic experiments, here is a readymade project and a machine that goes with it.

Nature's generator works on the same basic principle as the man-made Van de Graaff machine-but differs remarkably in its geometry and details of construction. The conventional Van de Graaff employs a pair of spherical electrodes, held apart by a cylindrical

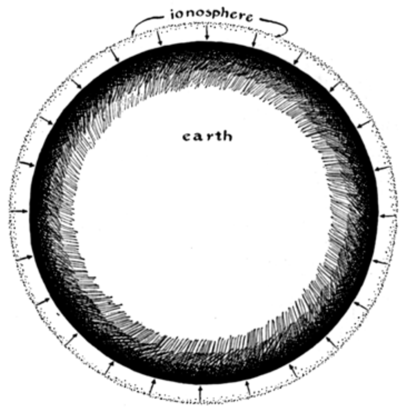

Figure 1: Principal components of nature's Van de Graaff generator

insulating column and charged by the action of a motor-driven belt. The arrangement resembles a big dumbbell. The belt "pumps" electrons out of one sphere and deposits them in the other. As the pumping action continues, an electric field builds up between the spheres. The voltage is limited only by the curvature of the collectors and the insulating properties of the column, belt and surrounding atmosphere. In nature's design, on the other hand, the parts of the generator take the form of concentric spheres. The earth, which is the negative electrode, is at the center. It is surrounded . by a hollow sphere of insulating material: the lower atmosphere. The insulator is in turn surrounded by the positive electrode: the ionosphere. A spherical pattern of thunderstorms within the insulator functions as the charging belt. The machine's effectiveness as a generator of high voltage leaves something to be desired because the atmosphere is a relatively poor insulator: its resistance amounts to only 200 ohms. Yet thunder- 6,;. storms do an astonishingly good job of keeping the electrodes charged.

Lightning, the counterpart of the . man-made machine's corona points, carries current amounting to thousands of amperes. On the average 100 strokes of lightning hit the earth every second. You can hear the resulting electromagnetic debris at any hour by hooking a long antenna to the input of an audio frequency amplifying system and turning up the volume [see "The Amateur Scientist; SCIENTIFIC AMERICAN, January, 1956]. It makes a sharp, buzzing s;. sound. The energy output of the 2,000 . to 6,000 thunderstorms in progress at any one time is sufficient to maintain an average potential of 360,000 volts between the earth and the ionosphere. This despite a leakage of current through the atmosphere of 1,800 amperes! The intensity of the field diminishes with height, but near the surface it amounts to about 100 volts per yard of altitude. Accordingly we walk around with our heads in air some 200 volts positive with respect to the ground at our feet [see "The Earth's Electricity," by James E. McDonald; SCIENTIFIC AMERICAN, April, 1953].

Given sufficient time, conductors insulated from the ground pick up the potential of the surrounding air. A negatively charged body attracts positive ions from the air until its negative charge is neutralized. Conversely, a positively charged body attracts negative ions. The time required for a body to reach electrical equilibrium with the surrounding air depends largely on its size and the concentration of ions naturally present in air. The amount of electricity that a body can accumulate its capacity for holding charge is also proportional to its size. Ellis's antenna tower was so big, and had lost so much negative charge to the surrounding air, that he was knocked off balance by the swarm of returning electrons. Had he touched a small object, say a metal ventilator or several hundred feet of wire, the current would doubtless have been so small he would not have felt it.

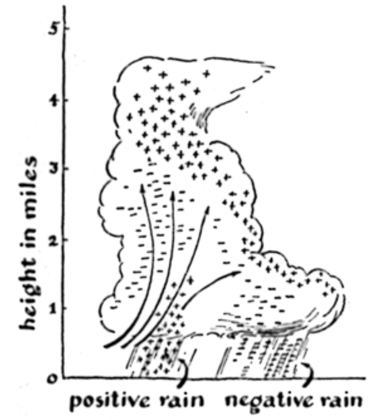

Figure 2: Distribution of charge in a thunderstorm

Several methods of measuring the intensity of the earth's field are based on the fact that conductors can reach electrical equilibrium with the surrounding air. These methods lend themselves to an interesting series of experiments. In principle the measurement is simple. You merely place a test structure (a few feet of wire will do) at a given height above the ground, insulate it from the earth, wait until it reaches electrical equilibrium with the air, and connect a voltmeter of appropriate sensitivity between the test structure and the earth. The meter reading is divided by the height in feet; the result is the field intensity in volts per foot. The field intensity varies considerably with location, topography, the hour of day and the state of the weather. Readings made at the top of mountains or steep hills average much higher than those made at sea or in prairie country. Conversely, observations made in valleys average somewhat lower. Usually the charge of the earth is negative, but under the trailing edge of a thunderstorm it is often positive. Here potential differences of 3,000 volts per foot have been recorded. The intensity of the earth's electrical field also varies during the day; this appears to be a consequence of the uneven distribution of the earth's land area. The number of thunderstorms reaches a peak when the continents of the Western Hemisphere are turned toward the sun; at that time Europe and Africa have just absorbed their daily quota of solar heat. This explanation, like many others concerning the generation and distribution of the earth's electric field, has not been tacked down as neatly as physical meteorologists would wish. Mori observations of the daily population of thunderstorms, together with corresponding information on the variation in field intensity, are needed.

Although the measurement of field intensity is simple in principle, it is made difficult in practice by the fact that considerable time may be required for a conductor to pick up charge

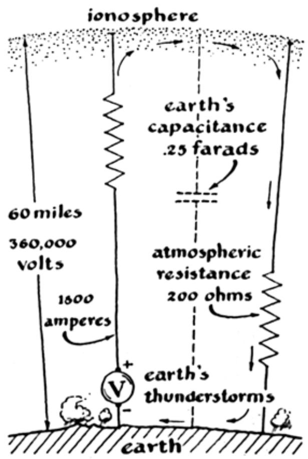

Figure 3: Diagram of the earth's electric circuit

from the surrounding air. Lord Kelvin devised ,' the first method of speeding up the process. He insulated a metal tank from the ground, filled it with water and arranged matters so that water would flow from a spray nozzle at the bottom, where the charge density is greatest per unit area. He called the arrangement a "water-dropper." The surface of each drop, immediately before it is detached from the stream, is an extension of the surface of the tank. Accordingly the potential difference between the drop and the air is equal to that between the tank and the air. When the drop is detached, it carries charge away. The process continues until equilibrium is established between the tank and the air. The test conductor need not consist solely of the tank. A relatively small water-dropper can be used for charging a test structure of any desired size. Garden sprays of the type which operate on compressed air supplied by a hand pump will charge a 30-yard length of wire in about 20 seconds. Fine spray is preferred to large drops because the higher ratio of droplet surface to volume not only conserves water but speeds the charging process.

The charging time can also be reduced by enriching the concentration of ions in the vicinity of the test structure. For example, a wire 10 to 15 feet long with a glass insulator at each end is suspended a yard or so above the ground between a pair of posts. A short length of the wire is then wrapped in string or paper that has been soaked in inflammable lead nitrate. When the string or paper is ignited, the flame produces ions in the vicinity of the wire; in a few seconds the potential of the wire will reach that of the ambient air. A torch waved in the vicinity of the wire will accomplish the same result but at some cost in terms of convenience. Where it is desirable to monitor the field continuously over long periods, radioactive materials may be called into service. A film of polonium electrolytically deposited on a wire will emit alpha particles which strongly ionize the surrounding air.

The practical measurement of field intensity is further complicated by the necessity of using measuring instruments of extreme sensitivity. Test conductors of reasonable size store little energy at low voltages at most a small fraction of a watt. If a substantial part of that little is consumed in driving the pointer of the measuring instrument, the accuracy of the reading will suffer. Lord Kelvin measured the potential of his water-dropper with a quadrant electrometer. This instrument consists of a metal vane suspended by a fine wire inside a metal structure which resembles a pillbox cut into four sectors. All the sectors are insulated from the ground, and sectors diametrically opposed to each other are wired together. The two pairs of sectors are then charged in opposite polarity by a battery, and the vane is connected to the test structure under measurement.

A small mirror cemented to the wire from which the vane is suspended serves as a pointer; a spot of light reflected from the mirror moves as the mirror turns. The vane moves in response to the electrostatic attraction and repulsion between its charge and that of the sectors. In the finest quadrant electrometers the wire supporting the vane is replaced by a quartz fiber which has been made a conductor by depositing a film of gold on it. When the vane is charged, it draws almost no current; yet the device is extremely sensitive to changes in voltage. Amateurs who go in for instrument making will find the construction of such an electrometer a challenging and rewarding enterprise.

Most modern electrometers are built around vacuum tubes of the screen-grid type. The basic circuit is simple. Bias voltage is connected between the cathode and grid of the tube through a high resistance. A microammeter is inserted into the plate lead; an ordinary battery supplies both screen-grid and plate voltage. The test structure is connected to the grid and the cathode is grounded. The intensity of the earth's field determines the charge on the grid and hence the strength of the plate current. The device is calibrated by connecting a source of known voltage to the grid and noting the resulting; deflection of the microammeter.

A number of precautions must be observed or the grid will draw an intolerable amount of current. Some current, for example, is contributed by positive ions which are ejected by the cathode and strike the grid. Another source of current is gas atoms ionized by electrons accelerated between the grid and plate. In addition, some of these electrons strike the plate with enough energy to produce soft X-rays, which in turn dislodge electrons from the grid. Light falling on the grid also ejects electrons from it. Finally, grid current tends to leak along the surface of the bulb.

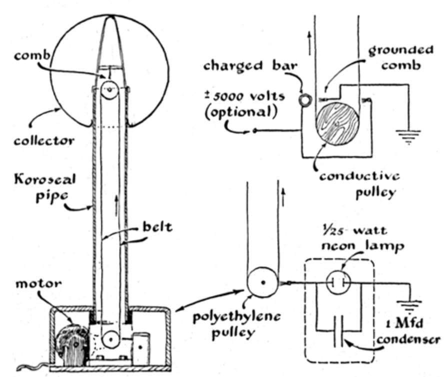

Figure 4: Van de Graaff generator with internal belt and external excitation

A number of techniques have been developed for reducing these currents. The production of positive ions can be reduced by operating the cathode at subnormal temperature. The grid can in effect be shielded by charging the screen grid to a higher positive potential (15 volts) than the plate (8 volts). This has the effect of repelling positive ions ejected by the cathode. Reduced plate voltage prevents electrons from acquiring enough energy for ionizing the residual gas in the tube and lowers the production of X-rays. Photoelectrons are eliminated by enclosing the tube assembly in a light-tight box. Surface leakage is reduced by washing the glass envelope with alcohol and dipping the area surrounding the terminal of the control grid in ceresin wax. In applications demanding maximum sensitivity air is evacuated from the light-tight box.

By meeting these circuit requirements and using a tube of special design, such as the-General Electric FP-54, it is possible to detect currents of 60 electrons per second. Other special electrometer tubes include the Victoreen 5803 and Raytheon 5886. The RCA 954 and 959 and the Western Electric 259-B types may also be used in all but the most exacting electrometer applications. For maximum sensitivity the grid must be tied to the cathode through a resistance on the order of 100,000 megohms. Such resistors are manufactured by the S. S. White Company, Victoreen and the International Resistance Company.

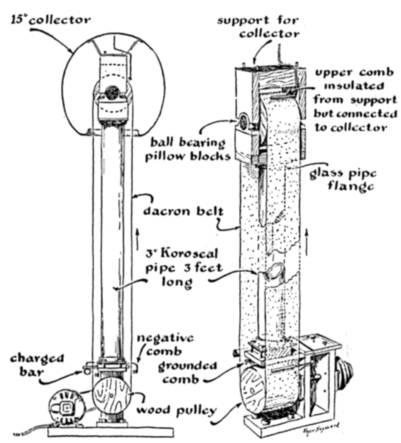

Figure 5: Van de Graaff generator with external belt and internal excitation

A third method of measuring the earth's field intensity eliminates the need for highly sensitive instruments by employing a device called a "field mill," which in effect transforms electrostatic charge into alternating current. Alternating current from the mill is amplified electronically and rectified. The output drives low-sensitivity direct-current ammeters, recorders and so on as desired. In effect, the field mill is comprised of a motor-driven variable capacitor which is connected in series with the capacitor represented by test structure, the earth's surface and the intervening air. As the capacity of the variable capacitor increases, current flows into it from the test structure. When the current of the variable capacitor decreases, current returns to the test structure. The frequency is made high in relation to the time required for the test structure to assume electrical equilibrium with the surrounding air. Hence the test structure remains substantially at the ambient potential, and energy lost through the weak oscillating current is not significant. Output from the mill is provided by voltage developed across a megohm resistor inserted between the variable capacitor and the test structure.

As usually constructed, the mill takes the form of a capacitor with three plates, two fixed and the third motor-driven. One plate is a shallow cylinder closed at the bottom and open at the top. The other two plates form the lid of the cylinder. Each of these plates looks rather like a two-bladed paddle; it consists of opposing quadrants joined at the apex One of them is mounted flush with the open end of the cylinder, but is insulated from it. This plate covers two quadrants of the cylinder, leaving two quadrants open. The open quadrants are-closed by the other plate, which is mounted directly above them. This last plate is keyed to the end of a shaft which extends through the assembly to the motor, fastened to the bottom of the box. When the shaft rotates, the blades of the plate alternately cover and expose the fixed plates. The rotating assembly is mounted on insulators and grounded through the megohm resistor across which the output voltage is developed. The alternating-current output is rectified by a synchronous reversing switch, or commutator, keyed to the opposite end of the motor shaft. By rectifying the output synchronously, both field polarity and intensity can be observed. The mill is calibrated by comparison with a known voltage. It is both rugged and portable. Special designs have been developed for use in aircraft, and have contributed significantly in recent years to this phase of meteorological research.

Franklin B. Lee, a chemical engineer and faculty member of the lrie County Technical Institute in Buffalo, N. Y., has built a number of small Van de Graaff machines and passes along the results of his experiments to amateurs who prefer to work with generators less bulky than the earth. "Two important pieces of information for the designer of Van de Graaff machines," he writes, "are, first, approximately 50 square inches of belt per second passing over the pulleys will produce one microampere of current; second, the maximum potential developed by the machine will be equal to 70,000 times the smallest radius of curvature of the collector in inches. Thus a perfect sphere 12 inches in diameter will have a theoretical limiting potential of 420,000 volts. Holes made in the sphere to admit the belt assembly alter the pattern of the field and reduce the theoretical maximum. The most effective compromise with the ideal shape for a practical collector is a spheroid slightly flattened at the bottom, with minimum radius of curvature located at a reasonable distance from the insulator to discourage sparking along the insulator surface [see "The Amateur Scientist"; SCIENTIFIC AMERICAN, April, 1955].

"The designer's choice of maximum voltage determines the size of the collector. To realize a large fraction of the theoretical limiting potential, the collector must be at least two or three diameters removed from other metallic parts. The distance should be greater if sharp-edged metal parts are present, and may be somewhat less if all parts are covered by a rounded metal shield of large radius of curvature. The opening which admits the belt to the collector ought not to be much larger than half the diameter of the collector and should be smoothly curved inward, generous radius of curvature.

"Although a high polish adds to the attractiveness of the collector, it is not essential. Minor surface imperfections, if well rounded, limit the maximum voltage only slightly. Sharp edges or burrs must be ground down. Lint and dust particles will reduce the voltage to 40 per cent of the theoretical maximum if they protrude from the surface as much as 1 per cent of the radius. Unpolished commercial aluminum spinnings, free of lint and dust, will collect about 85 per cent of the theoretical maximum. A high polish will increase the voltage another 1 per cent. The concentration of charge around the hole through which the belt enters accounts for the remaining 14 per cent, a quantity which varies, of course, with the size of the hole and its distance from other conductors.

"The hemispheres from which my collectors have been assembled were procured from a local metal-spinner who, if not too busy, will turn them out for $4.50 each, a reasonable price considering the fact that he pays $2 for the 14-gauge blanks. I had to furnish the wooden die on which the parts were spun. They would otherwise have cost on the order of $25. Incidentally, I will be glad to supply any number of 12-inch hemispheres at cost plus postage plus 75 cents per pair for handling, boxing and so on.

"Selection of the desired current output determines the size of the belt and the speed at which it must run. Meeting this specification is not so simple as it might seem offhand, because the properties of the materials used for the belt and its driving assembly enforce speed limits on both the belt and the shaft bearings. For maximum current one should in theory use the highest possible belt speed. But there are disadvantages in running belts faster than about 100 feet per second. Higher speeds aggravate the tendency of belts to fray at the edges and to come apart at the splices. At high speeds, particularly in the case of small pulleys, extreme tension must be maintained; this leads to bearing problems. Lubrication difficulties limit the shaft speed of sleeve bearings to about 5,000 revolutions per minute. The noise level of ball bearings becomes annoying above this speed unless special steps are taken to minimize it. At belt speeds above 100 feet per second appreciable amounts of power are lost through air friction. Finally, part of the charge appears to be 'blown, off the belt at excessive speeds a phenomenon which I do not wish to be called on to explain.

"Belts may be made of almost any insulating material: paper, cloth, rubber, plastic and so on. Rubber, because of its poor resistance to ozone, has a h limited life, but with used inner tubes 't costing so little the inducement to improve on it is slight. Rayon, nylon, Dacron and cloth (made into belts with acetone cement) are almost as good. Incidentally, when these materials are substituted for rubber, the position of the corona-collecting combs must be shifted. Cloth belts are more durable than rubber, are quieter and require less driving power, but tend to fray at the edges. This is easily remedied by a coat of lacquer. All things considered, I find that belts of neoprene joined with a diagonal splice are a good compromise.

"The upper pulley must be made of a material which is a good electrical c0nductor, such as wood or Bakelite Surprised? At such voltages these materials are very good conductors for the small currents involved. Scrap plywood may be glued together to make a highly satisfactory wooden pulley. The lower pulley should also be electrically conducting if. a separate 5,000 to 10,000-volt d.c. power supply is used for spraying charge onto the belt. If the machine is to be self-excited (that is, if the belt is to be energized by friction), the lower pulley should either be coated with or constructed of a material of extremely high resistivity. A 1/32-inch thickness of polyethylene makes a splendid covering for small wooden pulleys. The pulleys should be turned with a slight crown, the edge making a snug fit with the inside of the polyethylene tube. The tube may be made by cutting the ends off a round squeeze bottle. The tube is simply pushed over the wooden core. The choice of pulley and belt material for self-excited machines determines the polarity of the collector charge. A rubber belt running on a lower pulley of polyethylene or polystyrene will usually pump electrons from the collector and hence charge it positively.

"The belts may run on either the inside or the outside of the insulating support. Economy, simplicity and high currents favor running them on the outside. Appearance and neatness of construction require them to be on the inside. The former arrangement permits the use of a small, relatively inexpensive insulator with low current leakage and minimum deterioration due to corona discharge (the source of ozone). It also permits use of the widest belt possible for a given opening in the collector. Problems arising from unequal potentials throughout the insulator are similarly minimized. All hygroscopic or fibrous materials should be avoided in the selection of the insulating column because they invite leakage through the moisture which forms on the surface. The material must also be selected with an eye to its mechanical properties: strength, stiffness and toughness. FinalIy, it should be readily available at a reasonable price. Tubing of polyester glass-fiber laminate or polyvinyl chloride meets these requirements and is available in standard pipe sizes. In the three-inch (diameter) size, it costs $2.60 per foot. Polyvinyl chloride is the less hygroscopic of the two and may be flanged or formed to other contours by heating it to its softening point in hot paraffin.

"Combs or corona points for applying charge to the belt may be contrived in great variety. Often a common pin or a single phonograph needle can be as effective as the most elaborate comb. A tuft of wire, bound at one end and sheared like a broom at the other, makes h a satisfactory comb, as does a small rectangle of wire screening. Care must be taken to avoid spraying areas of the belt with unwanted charge. This may happen if charges are permitted to mix on the front and back of the belt near the pulleys. The problem is met by mounting the combs on fixtures which provide easy adjustment over a wide range of positions, and by selecting comb sizes which restrict the areas that are sprayed with charge."

The simple Newtonian telescope that is shown at the right is submitted by W. Gorrell, Jr., of Buffalo, Wyo. A local school, having purchased a telescope kit and made a three-inch mirror, was stumped for an adequate mounting. On appeal, Gorrell solved the problem by a visit to a local automobile junkyard plus a few evenings of labor. The gadget he picked up in the junkyard should interest any amateur on the verge of assembling a small equatorial mounting.

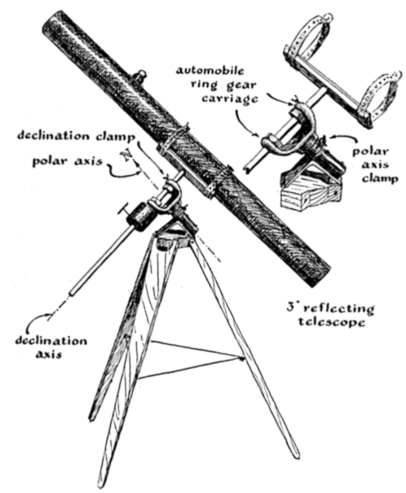

Figure 6: a simple equatorial mounting for a small telescope

The lucky find is a "ring-gear carriage," a component of the transmission h assembly in most pre-automatic-shift cars. "The holes through the yoke end," Gorrell writes, "are aligned precisely and make a snug fit with a .75-inch shaft. The bottom of the part is faced off. Both the outside and inside are turned. The shoulder and the top surface are nicely faced. I used only one of the inside bores (the smaller one), for which I turned a piece of pipe to fit. A brass collar on the pipe takes the downward thrust of the instrument.

"The ring-gear carriage turns in a short length of pipe, which is welded to an angle-iron base as shown. The 45-degree angle of the base is close enough to that of our latitude (44 degrees, 21 minutes) so that a slight tilt of the tripod compensates for the difference.

"Since the entire rig weighs only a few pounds and the center of the yoke is the center of balance between the 'scope and the counterweight, the instrument can be lifted off the tripod yoke, counterweight and all and reassembled without touching a single screw or clamp."

Bibliography

AMATEUR TELESCOPE MAKING: BOOK I. Edited by Albert G. Ingalls. Scientific American, Inc., 1951.

ELECTRONICS: EXPERIMENTAL TECHNIQUES. William C. Elmore and Matthew Sands. McGraw-Hill Book Company, 1949.

PHYSICAL METEOROLOGY John Clark Johnson. The Technology Press and John Wiley & Sons, Inc., 1954.

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Various induction machines have been designed for performing the sequence of operations automatically and with considerable speed. In these machines the "carriers" take the form of thin metallic sheets instead of balls, and the capacitors also are metal sheets, called field plates.

An early form of the machine, patented in 1860 by C. F. Varley of England, is easy to construct [*see Figure 3*]. It consists of a pair of field plates cemented to a square slab of lucite surmounted by a rotating disk of lucite to which six or more sectors of aluminum foil are cemented. Two brushes (of tinsel) momentarily connect opposite sectors, the carriers, with their respective field plates as each carrier enters the region of its plate. A similar pair of brushes again make contact with opposing pairs of carriers as they move from the region of the field plates. A pair of "corona" combs-quarter-inch metal rods fitted with steel phonograph needles spaced half an inch apart-graze the carriers at positions intermediate between the two sets of brushes. The machine's electrical output flows from the combs to a pair of spheres an inch or so in diameter which comprise a spark gap.

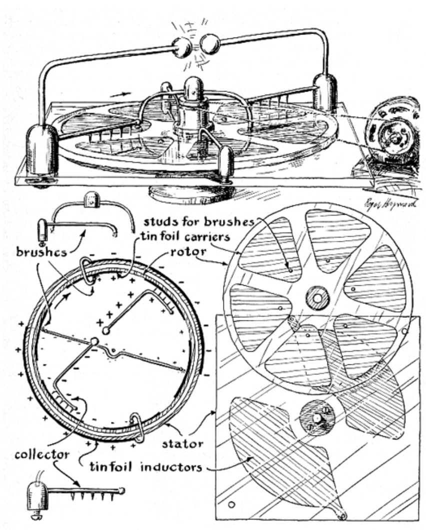

Figure 3: Varley's induction generator

The lower left diagram illustrates the action. Assume a charge on the field plates [*outer solid segments*]. Electrons flow into the carrier at the left, leaving the right-hand carrier with a positive charge. Work is now expended in moving the carriers "up the potential hill" to the opposite field plates. Here they make contact with the brushes and part of their newly acquired energy flows into the field plates; electrons enter the field plate [*top of drawing*] from the negatively charged carrier, while the opposite carrier withdraws electrons from the lower plate. The succeeding action of all carriers is similar. After a short period of operation the combs reach ionizing potential, and energy flows from the carriers to the gap, where vigorous sparking occurs.

The machine is not very efficient. This can be demonstrated by observing its operation in a dark room. The rotating carriers appear as a blurred disk of phosphorescence in colors ranging from greenish-blue through violet, while the field plates are outlined sharply in purple. Corona discharge at the combs is $2 brilliant. This display means that electrons are streaming from the thin, sharp edges of the foil and the points of the comb carrying negative charge and into those parts carrying a positive charge. Considered as an electrical "pump," the machine is leaky and thus wastes energy.

The corona effect is explained by the geometry of the machine's conducting parts. Unless distorted by another charge, the electric field radiates into, space uniformly in all directions from a point charge. If the charge is enclosed by a conductor, the lines of force always emerge perpendicular to its surface. In the case of a spherical conductor (in effect, an enlarged point) the lines are, therefore, distributed uniformly over the surface. When the sphere is distorted to an egg shape, however, the lines bunch up at the little end and thin out at the big end-because they must emerge everywhere at a right angle to the surface. Crowding at the little end becomes more pronounced as the radius of the "point" is made smaller. This is another way of saying that the intensity of the field, or the potential gradient, increases inversely with respect to the radius of the conductor; in theory it would approach infinity at the point of a perfect needle. Even in practice, finely made points can concentrate fields of astonishing intensity. The exquisite needles used in field-emission microscopes [see "A New Microscope," by Erwin W. Müller, SCIENTIFIC AMERICAN, May, 1952] create field intensities of 750 million volts per inch in the immediate vicinity of the point-although the instrument operates from a power supply of only 5,000 volts! At this field intensity electrons are literally ripped from the metal point and ejected radially into space. Gas, if present in the tube, becomes heavily ionized. The collecting combs of the Varley machine similarly ionize adjacent air, negative charges being carried by dislodged electrons and positive charges by the ions.

In the early years of this century the Wimshurst generator, similar in basic principle to the Varley but carrying one or more pairs of disks that rotate in opposite directions, was a favored source of power for X-ray machines and other devices requiring relatively small amounts of current at high voltage. The largest machines carried as many as 12 pairs of disks seven feet in diameter and delivered potentials on the order of 200,000 volts.

The Wimshurst and other electrostatic generators of this era could not reach the million-volt range. By 1920 they had been largely replaced by electromagnetic induction coils and transformers as sources of high-voltage power.

The modern era of electrostatics began in 1929. In that year Robert J. Van de Graaff, a young Rhodes scholar from Oxford University who was working at Princeton as a National Research Fellow, invented the electrostatic belt generator