Chapter I. Electrostatic Accelerators

I.1 Scientific Motivation

It was Rutherford who fired the pistol to start the race to build accelerators of ever increasing energy. By 1928 his reputation as a founding father of nuclear physics was firmly established and, as a reward, had just been made president of the Royal Society of England. In his presidential address he said, "I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances." These were inspiring words and no doubt they focused the attention of many new minds as well as encouraging others who were already working on the problem.

At that time, the cyclotron had yet to be invented — though that was to be only a year or two later. Two acceleration methods had been proposed: the linear accelerator by Ising and the ray transformer of Wideroe. We shall devote later chapters to these machines, but when Rutherford made his plea they would have to wait many years before they became practical. Meanwhile many nuclear physicists pinned their faith in the electrostatic route — the simplest concept of all — acceleration between the terminals of an electrostatic high voltage generator. Notable among these were Cockcroft and Walton at the Cavendish Laboratory in Cambridge.

One of the first applications of electrostatic accelerators at the Cavendish was to fire particles into the nucleus. It had been calculated from classical mechanics that a particle would have to have a very high energy to penetrate the nucleus. Rutherford had used 10 MeV alpha particles from radioactive decay for his famous scattering experiments and it was argued that if the nucleus can emit particles with 10 MeV energy, the forces which bind it together must be strong enough to repel any particle approaching it with a smaller energy. Ideas for suitable high voltage generators were very much in their infancy and it was impossible to imagine matching the 10 MeV energies of alpha particles. Even if someone had succeeded in making a 10 MeV power supply the problems of avoiding catastrophic breakdown to ground would have been challenging. Sparks can jump meters at that voltage. There was a long way to go.

Fig. 1.1 The Cavendish Laboratory, where the landmark experiments of Cockcroft and Walton took place. Note the ecclesiastic style of university buildings of that time. This laboratory was the setting for the many wonderful innovations and developments described in the sidebar.

Sir John Douglas Cockcroft (1897–1967)

English physicist
Nobel Prize for Physics, 1951 (shared with Walton)
Co-inventor of the Cockcroft-Walton high voltage generator

John Cockcroft was the eldest of five sons of a Yorkshire miller. He won a scholarship to study mathematics at Manchester University but became fascinated by atomic physics after reading the work of J.J. Thompson and Rutherford — then at Manchester. His studies were interrupted by the First World War, in which he served as a junior officer, and was the only survivor of his unit during bitter fighting at a forward post on the Western Front.

After completing a Manchester degree in electrical engineering, he joined the Metropolitan Vickers Company but was eventually sent to Cambridge to improve his mathematics. There, he again came across Rutherford, who promised to take him into the Cavendish if he got a “first” in mathematics. Meanwhile he was to be “spare time honorary electrical engineer.” He first worked with the famous Russian, Kapitza, who was intent on producing intense magnetic fields by short circuiting a very large generator through a single turn of copper. Cockcroft was able to draw on the experience of his Metropolitan Vickers friends to help. Kapitza’s bold use of electrical machinery perhaps inspired Cockcroft to take the direct approach when the time came for him to accelerate protons. Together with Walton he invented the high voltage generator that bears their name. There were shades of Rutherford’s gift for improvisation when they scoured the countryside for the discarded glass sight glasses from petrol pumps, which they stacked up to form the acceleration tube.

Cockcroft and Walton used this apparatus in 1932 for their momentous experiment: the first artificial transmutation of lithium into helium, which was to much later gain them the Nobel Prize.

Unlike his retiring partner, Cockcroft continued at the Cavendish until, like Oliphant, his skills were redirected at the start of the Second World War towards securing Britain’s air defenses. He was then sent to Canada to become director of the Montreal and Chalk River Laboratories.

His post-war career continued when, as Director of the Harwell Atomic Energy Research Establishment, he led the development of nuclear energy for peaceful and defense purposes. He was much respected by his 6,000 or so staff, many of whom, however junior, would have a tale to tell of how he had wandered unannounced into their workshop or laboratory to show an interest in what they were doing. After a few encouraging words, he would make miniscule crisp notes in a famous little black book about what he should remember and attend to in order to help their efforts.

Ernest T.S. Walton (1903–1995)

Irish physicist
Nobel Prize for Physics, 1951 (shared with Cockcroft)
Co-inventor of the Cockcroft-Walton high voltage generator

Ernest Thomas Sinton Walton was born at Dungarvan, County Waterford on the south coast of Ireland on October 6th, 1903, the son of a Methodist minister from County Tipperary. In 1915 he was sent as a boarder to the Methodist College, Belfast, where he excelled in mathematics and science. In 1922 he entered Trinity College Dublin and graduated in 1926.

In 1927, he went to Cambridge University to work in the Cavendish Laboratory under Lord Rutherford, receiving his PhD in 1931. At the Cavendish Laboratory, he worked on methods for producing fast particles, first on a linear accelerator and then what was later to become known as the betatron. He followed this with work done jointly with J.D. Cockcroft on the direct method of producing fast particles by the use of high voltages. Together they invented a column of diodes, known to this day as the Cockcroft-Walton generator, which could multiply a modest voltage into several hundred thousand volts. Fast protons were accelerated down an evacuated glass column between the terminals of this device. The protons were used to bombard and disintegrate the nucleus of the lithium atom. The products were identified as helium nuclei.

This was the first occasion on which an atomic nucleus of one element had been artificially changed into that of another element — the so-called “splitting of the atom.” This discovery, for which he was later to receive the Nobel Prize, was arguably the most important and momentous made by Rutherford’s brilliant team of researchers at the Cavendish Laboratory in the mid 1930s.

A reserved and retiring man, Walton was soon to leave Cambridge. In 1934 he returned to Trinity College, Dublin, as Fellow and then Professor of Physics.

But as quantum mechanics began to be understood, George Gamow realized that the uncertainty principle allowed particles to escape from nuclei at a lower energy and that this would explain radioactive decay. E. Condon and R.W. Gurney had independently come to the same conclusion. Gamow then turned the argument around and predicted that quantum mechanics would allow nuclear particles to enter the nucleus at significantly lower energies than had been thought. He estimated that 300 keV might be enough. (See box on the Coulomb Barrier.) Gamow’s work became the guiding light for John Cockcroft and Ernest Walton of Cambridge, who set about building an electrostatic generator for this voltage.

The Cavendish Laboratory in the Time of Cockcroft and Walton

In a narrow lane opposite Corpus Christi College, Cambridge, its site chosen to protect it from the vibration of traffic, stands the Cavendish Laboratory. It was established in 1871 and its first professor was the great James Clerk Maxwell who, being a great admirer of Cavendish's work on electricity, christened the laboratory after him. From the outset it was to be a laboratory in which the highest standards of experimental physics were to be observed using the simplest of apparatus — often hand built by the researcher himself.

Accelerators began to be of importance at the Cavendish Laboratory in 1927. Nobel prize-winner Ernest Rutherford was then its director, following in the footsteps of Maxwell, Lord Rayleigh and J.J. Thomson, each of whom had made revolutionary contributions to our understanding of physics.

One might not expect to find the atmosphere among such eminent physicists to be light hearted, yet the Cavendish at the end of the 20s could be quite informal. The working day hardly started before ten in the morning, and every evening at six, a technician would solemnly go the rounds to switch off all lights and power supplies, even if this meant that a crucial measurement had to be interrupted and repeated the next day. A visiting American is reported to have written to Thomson that by US standards this would be seen as "sloth and indolence" — but that was the style; and Thomson held that experiment should always be followed by a respectable period of reflection.

The frequent colloquia and seminars at the Cavendish were of the highest standard and invited speakers came from all over the international world of physics. In Rutherford's time there were as many as fifty graduates studying for PhD's and it is not surprising that there was also some fun to be had. The more senior researchers were not above joining in, and Peter Kapitza, then working at the Cavendish, describes the lab's annual dinner where: "you could do anything you liked at table — squeal, yell, and so on. After the toasts it was very funny to see such famous luminaries as Thomson and Rutherford standing on their chairs and singing at the top of their voices."

For Rutherford all science, indeed all physics other than the search for atomic structure, was "mere stamp-collecting." He was famous for employing only the simplest of apparatus. It was perhaps then a surprise that he pressed for expensive electrical equipment to provide a steady stream of charged particles for research at the Cavendish, but his research seemed to have reached an impasse. It was known then how strong the forces confining the positive charges of protons in the nucleus must be and it seemed clear that many MeV of energy would be needed for a particle to break in and probe the structure of the nucleus. After all, the particles emitted from nuclear decay have energies of this magnitude. Electrical industry did not seem capable of producing steady voltage of this size and attempts by Walton to build betatrons and linacs had not been successful. In the end, the energy needed did not turn out to be that high and was just within the reach of electrostatic machines. The way in which Rutherford came to be convinced of this is interesting and says much for the effective international communication of ideas at the time as well as Rutherford's open mind.

In the years after the First World War experimental research into the structure of the atom was centred in Germany, France and the United Kingdom. Rutherford, first at Manchester, then at the Cavendish, was the focal point for the majority of the experimental work while Bohr's institute in Copenhagen headed the theoretical work, hosting the fathers of quantum mechanics — Heisenberg, Schrödinger and Pauli. Copenhagen was not unlike the Cavendish in its informality and lively social life. There was a healthy cross-fertilisation between the two centres and it was thanks to a friendship between Mott of Cambridge and Gamow, a Ukrainian physicist at Copenhagen, that the idea of applying wave mechanics to nuclear disintegration reached Cambridge.

Gamow inherited socially colourful and rather bohemian characteristics from his Odessa family. His father had taught the adolescent Trotsky, and Gamow junior had taught Red Army artillerymen the basics of physics. His bedroom wall boasted a framed verse "when the morning rises red, it is best to lie in bed." He nevertheless was both brilliant and productive physicist and soon moved on to Bohr's Institute by way of Göttingen. His contribution to the work of Rutherford's Cavendish was however crucial.

It had seemed impossible to explain how the alpha particles that emerged from the nucleus in radioactive decay could get out against the strong forces binding the nucleus together, and this had been a major stumbling block in understanding the atom and its structure. Gamow showed that the uncertainty principle and the wave nature of particles would allow a charged particle a small probability to enter or leave at an energy of 300 keV: much smaller than had been previously thought necessary (see sidebar on the Coulomb Barrier).

Mott and Hartree from the Cavendish visited Copenhagen and, although with hardly a word in common, were thrilled with Gamow's tales of the Russian Revolution. They were even more interested in his theory suggesting the nuclear barrier might be penetrated and encouraged him to bring it with him to the Cavendish.

Rutherford was naturally wary of new-fangled theories such as quantum theory and wave mechanics, but Gamow convinced Rutherford of his ideas during a visit to the Cavendish. When Cockcroft, then supervising the work of Walton and Allibone, was asked for five hundred pounds for an electrostatic generator to produce the 300 keV that had Gamow calculated, he readily agreed.

Allibone, like Cockcroft, had previously worked at Metro Vickers and was no stranger to electrical machinery, while Walton had been already trying to build other accelerators. The work of constructing the high voltage generator started and, when concluded, made it possible to induce a series of nuclear reactions with accelerated particles. This brought experimental physics at the Cavendish in the 1930s out of the era of string, sealing wax and glass blowing. Research directors had to be convinced, financial approval sought and the professional help of consulting engineers engaged. Of course similar changes in the approach to experiments were also underway in Lawrence's laboratory in California.

At the same time, a previous colleague of Rutherford from Manchester, Hans Geiger, had invented an electronic tube to count particles. This, championed by Chadwick at the Cavendish, together with Cockcroft and Walton's electrostatic accelerator, brought a whole new dimension to the speed and accuracy of observation.

After pioneering atomic structure research, the Cavendish went on to produce four more Nobel laureates including prizes for unravelling the structure of DNA. It remains at the cutting edge of research in the UK.

ENGINES OF DISCOVERY - A Century of Particle Accelerators

The Coulomb Barrier

It has been known ever since the time of Coulomb that two like charges repel with a force that is inversely proportional to the distance between them. This is just like gravity but, of course, the force repels rather than attracts. If one fires a proton at a nucleus it will be subject to a repulsive force until it is "inside the nucleus" where the very strong (but short range) nuclear attractive force between protons takes over. In the opposite direction, when a nuclear reaction occurs expelling particles this short range force must first be overcome to breach the Coulomb barrier. Even in the time of Cockcroft and Walton, one had a fair idea of the size of a nucleus and it was possible to estimate the height of the Coulomb barrier. For light nuclei it is about 1 MeV and too high for early electrostatic machines to penetrate.

But that is a classical calculation: sub-atomic particles do not obey classical physics laws. In fact, quantum mechanics correctly predicts that even if the incoming proton does not have enough energy to get over the Coulomb barrier it can, with some probability of success, tunnel right through it. It was Gamow who first realized and estimated this tunneling. He predicted that even with only 300 keV the probability of barrier penetration was significant — opening the way to Cockcroft and Walton's famous experiments in the 1930s.

I.2 Voltage Multiplying Columns

Cockcroft and Walton's accelerator was based upon the idea of a voltage multiplying column (Fig. 1.2). Normal alternating current was first rectified (converted to direct current) and then applied to a number of large condensers (capacitors). The condensers, each bearing a voltage of a few hundred volts, were then connected in series so the voltage of each one added to the next. The combined voltage, in this case 600 kV, was then connected to an accelerating column in order to accelerate protons.

Their first publication, in 1932, was followed a few months later by another describing the very first man-made nuclear reaction. In this, a proton was added to a lithium atom to produce Be-8 that decays to 2 helium nuclei. In fact this crucial experiment used their second accelerating column. They had treated Gamow's figure of 300 keV with more caution than it deserved and had become fascinated with the task of going to 600 keV or more. They were bent upon improving their machine even further before making the measurements but Rutherford, the head of the Cavendish at the time, stepped in and insisted that they try the experiment without waiting for these improvements. In fact, even their first machine would have been adequate, for Gamow had been very correct in his estimates! Cockcroft and Walton were honored, much later, by receiving the Nobel Prize in 1951.

In the years that followed many devices were constructed, based upon the concept of the voltage multiplying column invented by Cockcroft and Walton. A 600 kV system was built in Ottawa in the late 30s and commercial systems were built by the Phillips Corporation before and after World War II. In the late 1960s a 2 MV system was installed at the Cavendish Laboratory and a pre-injector of 750 kV was built, and used, at the National Accelerator Laboratory (now Fermilab) in Batavia, Illinois (Fig. 1.3). This 2 MV column is about as far as one can go with a device in the open air before spark breakdown occurs. Enclosed systems, employing high pressure insulating gases, have achieved 6 MV. There was always a need for even higher energy and improvement in reliability and ease of operation.

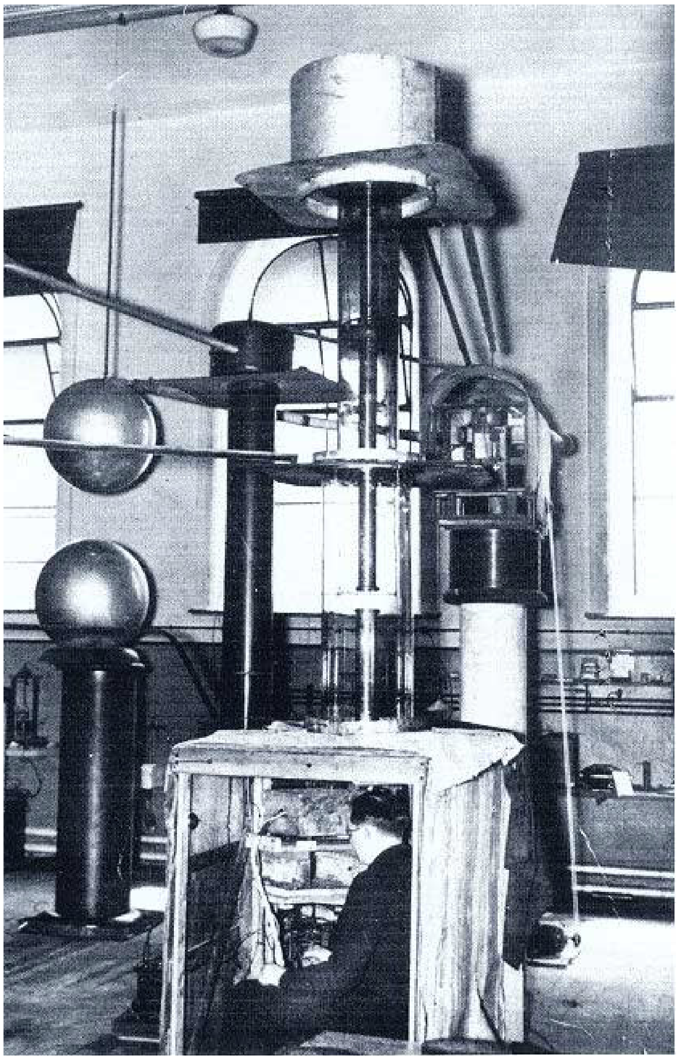


Fig. 1.2 The original Cockcroft-Walton installation at the Cavendish Laboratory in Cambridge. Walton is sitting in the observation cubicle (experimental area) immediately below the acceleration tube, which was covered with black velvet so that the faint scintillations might be observed by the detector.

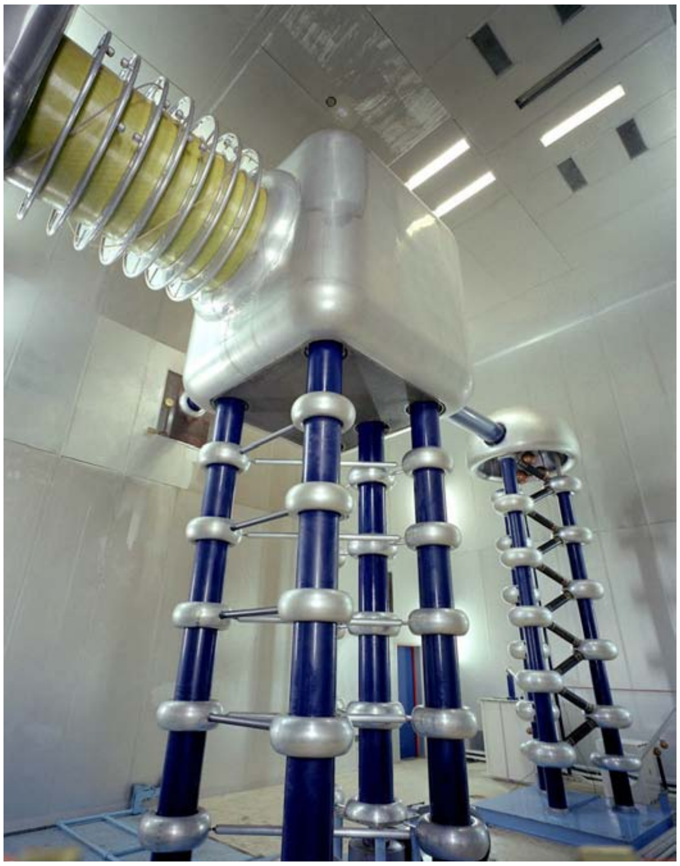


Fig. 1.3 The Cockcroft-Walton pre-accelerator, built in the late 1960s, at the National Accelerator Laboratory in Batavia, Illinois. This very large and expensive installation provided the voltage for the first tiny step in the acceleration of protons to energies of hundreds of GeV.

Robert Jemison Van de Graaff (1901–1967)

American physicist
Inventor of a high voltage generator used as an accelerator

Robert Van de Graaff was born in Tuscaloosa, Alabama to Minnie Cherokee Hargrove and Adrian Sebastian Van de Graaff. He followed a degree course in mechanical engineering before starting work in the research department of the Alabama Power Company. It seems that Alabama was not at that time crowded with young men wanting to pursue their studies abroad and he was fortunate enough to get a place to study at the Sorbonne in Paris from 1924 to 1925, where he attended lectures by Marie Curie on radiation. In 1925 he went to Oxford University in England as a Rhodes Scholar, where he received a PhD in physics. It was there that he became aware of the plea of Ernest Rutherford that particles might someday be reliably accelerated to speeds sufficient to disintegrate nuclei.

Like Wideroe (see sidebar in Chapter III) he was inspired to respond to this challenge, but in quite a different way. In his physics classes, Van de Graaff would certainly have seen electrostatic machines, in which charge, sprayed on a metallic segment, could be transported and extracted onto a high voltage terminal. He extended this idea to use a moving belt to charge up a sphere. An ion source, within the sphere, generated particles, which were then accelerated as they traveled down to ground potential through an evacuated column.

In 1929 he returned to the United States to join the Palmer Physics Laboratory at Princeton and constructed the first working model of an electrostatic accelerator, which developed 80,000 volts. Improvements were made to the basic design and in 1931, at the inaugural dinner of the American Institute of Physics, a demonstration model was exhibited that produced over 1,000,000 volts.

It was later realized by Bennet in 1937 and, even later, by Alvarez in 1951, that by using a tandem Van de Graaff to accelerate negatively-charged ions to a high voltage and then stripping them of their charges with a foil, they would return to earth potential with twice the voltage of the generator.

At the time of his death there were over 500 Van de Graaff particle accelerators in use in more than 30 countries.

I.3 Silk Belts

Even before Cockcroft and Walton, Robert Van de Graaff, then a mechanical engineer studying physics at the Sorbonne, was inspired by a lecture given in 1924 by the very famous Louis de Broglie. Like Rutherford, De Broglie hoped for a machine to allow the careful and controlled study of nuclear particles and van de Graaff immediately set himself the task of building such a machine. From 1925–1929 he was at Oxford (on a Rhodes scholarship) and during this time he developed the concept that, ever since, has been called the Van de Graaff generator. (See sidebar for Van de Graaff and Fig. 1.4.)

In 1929 he went to Princeton, on a National Research Council Fellowship, and during this year built the first working model (only 80 kV). His idea was that the machine would transport charge mechanically (all other accelerators, before and since, have been purely electrical). He sprayed charge on a moving belt of pure silk which transported it to an upper terminal where it was removed. The device built up charge and hence a voltage on the terminal which was in the form of a large sphere: the shape that best holds charge without creating a spark. This voltage was then applied (as in Cockcroft-Walton machines) to an accelerating column down which particles accelerated from high voltage to ground. In later higher voltage versions of the machine, the belt was housed inside an insulating gas, sulfur hexafluoride, to minimize sparking.

Van de Graff's first published device achieved 1.5 MeV. This was in 1931 and actually before Cockcroft

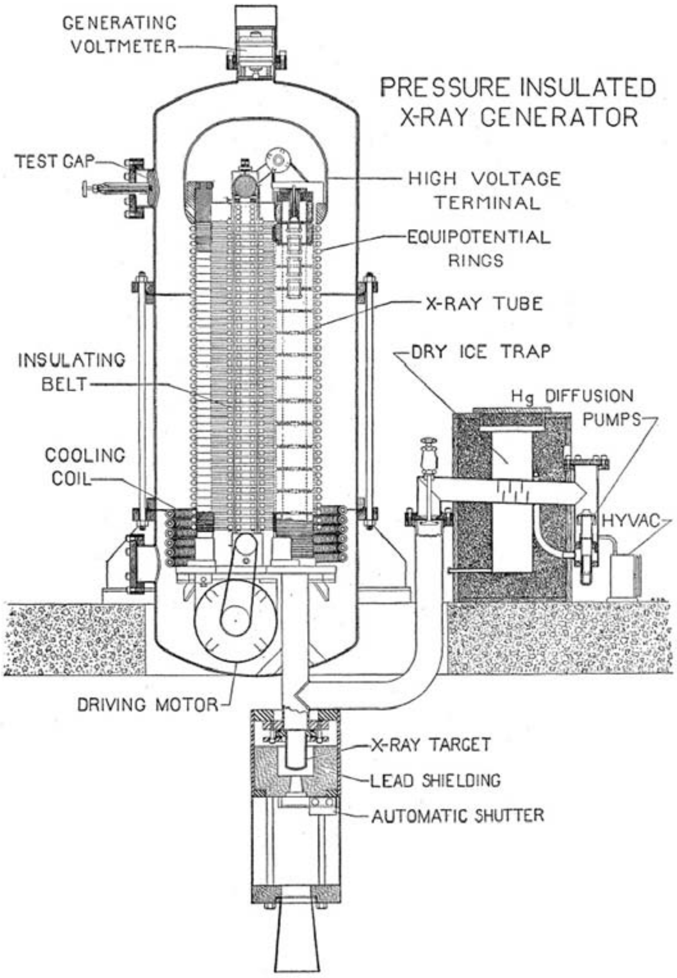


Fig. 1.4 Line drawing of a Van de Graaff accelerator — part of one of Van de Graaff's patent applications around 1930.

and Walton completed their work. It was a dual device, 2 m tall that had two 5.6 cm silk belts feeding two spherical upper terminals. We are told it only cost $100 and it was patented a few months later.

The concept was immediately picked up by Gregory Breit, Odd Dahl, and Merle Tuve at the Department of Terrestrial Magnetism of the Carnegie Institute in Washington, who made many technical contributions that greatly improved the machines. (See sidebar for Dahl.) Soon they had constructed a device for a voltage of 1.2 MeV which, unlike Van de Graaff's, had a single two-meter upper sphere. It was assembled in the open air and sparked whenever an insect alighted on the sphere. Typical operating voltage, including the effect of insects, was only 600 kV. They later built a much more reliable device indoors which also had a two-meter upper terminal and produced 1.2 MeV.

Van de Graaff moved to MIT in 1931 and built a very large generator in a former balloon hangar (Fig. 1.5). The upper terminals were 4.6 m in diameter, 6.7 m high. Paper was used for the belt rather than silk and the voltage between the two terminals was 5.1 MV. It was difficult to maintain smooth non-sparking spheres because of pigeons living in the roof of the hangar. The effect of their droppings prompted some very dramatic pictures (Fig. 1.6).

Odd Dahl (1899–1994)

Norwegian physicist
Builder of three Van de Graaffs, a betatron and a nuclear reactor in Norway
Led the design of the first CERN Proton Synchrotron

Odd Dahl was one of the disproportionate number of Norwegians who pioneered novel and successful accelerator projects. With only a modest formal education he joined Amundsen's 1922 Arctic expedition as an air pilot. After his plane was damaged beyond repair during a difficult takeoff from an ice floe, he spent the following two shipbound years learning physics and developing oceanographic instruments. In 1926 he joined the Carnegie Institution in Washington where, working with Merle Tuve and Lawrence Hafstad, he developed instruments for the study of terrestrial magnetism of the atmospheric Kennedy-Heaviside layer and for nuclear physics.

Returning home to the Christian Michelsen Institute in Bergen in 1935, he built a new series of three Van de Graaff machines, a betatron and, in the early days after World War II constructed Norway's first reactor without access to classified work.

In the very early days of CERN (1951) he was appointed to build their first 10 GeV proton synchrotron but, after hearing of the discovery of alternating gradient focusing during a historic meeting at Brookhaven with its inventors, Courant, Livingston and Snyder, he returned to tell the CERN team that "you must drop everything and work only on this."

Thanks to his courage and leadership, CERN physicists were able to switch to a machine of three times the energy, bringing Europe on a par with events in the USA. He was mentor to Kjell Johnsen (see sidebar in Chapter VI on Johnsen), another Norwegian whom he recruited in the early days of CERN and who went on to build the ISR project. Johnsen said of him "he accepted only challenging tasks and his intuition never failed him" — a comment that might equally apply to Johnsen himself and to another Norwegian, Bjorn Wiik (see sidebar in Chapter VI on Wiik) who was later to lead the HERA project at DESY.

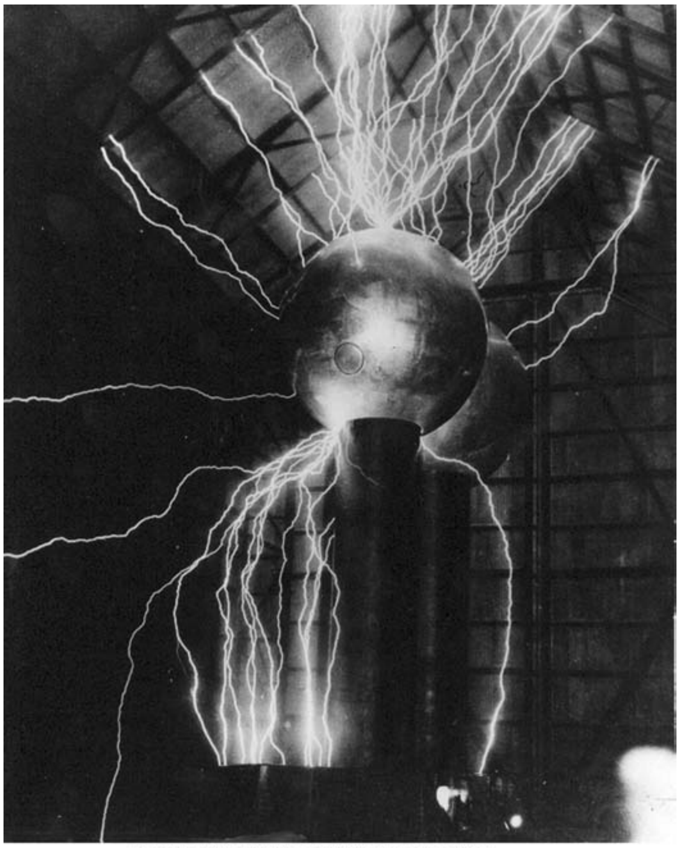
I.4 Wisconsin Advances

About this time (1932) development of electrostatic accelerators also started at the University of Wisconsin and was pioneered by G.G. Havens. It was here that some improvements were built in to avoid the fickle

THE GENERATOR IN THE HANGAR AT ROUND HILL

©MIT Museum All rights reserved

Fig. 1.5 Van de Graaff's very large accelerator built at MIT's Round Hill Experiment Station in the early 1930s. The spheres stood 43 feet above the ground, supported on steel trucks that ran on a railroad track to make it possible to change the striking distance.



AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

©MIT Museum All rights reserved

Fig. 1.6 Because their electrodes were very smooth and almost perfect spheres, Van de Graaff generators did not normally spark. However, the installation at Round Hill was in an open-air hangar, frequented by pigeons, and here we see the effect of pigeon droppings.

nature of the earlier machines. The first of these machines had not reached a high enough voltage to induce nuclear reactions, but by 1933, Havens and his students (including Donald Kerst, who invented the betatron, and Raymond Herb, about whom we shall say much more) had achieved 1 MeV and reproduced the nuclear reaction that Cockcroft and Walton had observed earlier.

In 1935, Raymond Herb, who had just returned from a summer at the Department of Terrestrial Magnetism, introduced the first of many technological advances in electrostatic machines. He took the original insulating vacuum tank of Van de Graaff and filled it with pressurized gases to improve the voltage holding capability of the charging belt and the accelerating column. He also put conducting rings along the accelerating column, which helped control the accelerating gradient. All modern machines use these two innovations. He went on to develop the mechanical engineering that allowed the whole machine to be cantilevered out to be operated horizontally. There were other technological advances too, which helped make the machines less expensive, easy to operate and highly reliable.

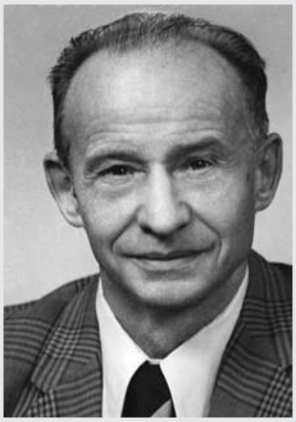
One of Ray Herb's most important inventions, first applied in 1965, was to change the charging belt from a continuous smooth belt to one with steel cylinders held apart by nylon insulating links in the form of a chain. These new drive systems were highly efficient, had a long life, needed little maintenance, provided extremely stable terminal voltage conditions and were in general far superior to the old belts. Herb called machines using these belts Pelletrons, and he was sufficiently enthusiastic and confident about the new machines to form a company to build them.

I.5 Tandems

It was W.H. Bennett, in 1935, who first realized that an electrostatic column would accelerate negative ions (neutral atoms with electrons added) from ground potential to the high voltage terminal — the opposite route to that taken by the positively charged ions that a Van de Graaff normally accelerated. If the electrons of the negative ions could be stripped of electrons by passing through a thin foil within the high voltage terminal, then the positively charged nuclei would be further accelerated as they returned down the column, thus apparently doubling the energy of a machine. In 1940, he patented the idea and in 1953 laid down in detail the design of a modern tandem accelerator. In 1951, Luis Alvarez, building on the work of the 30s,

Raymond Herb (1908–1996)

American physicist
Honorary degrees from Basel, Sao Paulo, Lund, and Wisconsin
Awarded the Bonner Prize of the American Physical Society
Member of the National Academy of Sciences



Born on a small farm in Wisconsin, as one of eight children, he did his undergraduate and graduate work at the University of Wisconsin, where he received his PhD in 1935. He joined the faculty of the University of Wisconsin from 1935 until his retirement in 1972. Except for one summer in 1935, spent at the Department of Terrestrial Magnetism in Washington, and the war years of 1940–1945, at the Radiation Laboratory at MIT, he spent his entire life in Wisconsin.

Although Ray Herb produced some fine nuclear physics with the electrostatic machines he built, his special talent was in the technical field, making these devices ever better. It is perhaps difficult for the outsider to really appreciate his contributions. One discovery was that the dielectric properties of air could be increased by adding carbon tetrachloride so that one could get to higher voltages in electrostatic machines; another, that by adding voltage controlling rings, corona points or resistors all around the accelerating columns, one could get to even higher voltages; and there were many other "small things" that made his machines the best in the world.

We describe in this chapter how Ray Herb, in 1965, established the National Electrostatics Company. Although the start was difficult, the company ultimately employed up to 140 people and produced 130 machines. The "selling" of these machines, for purposes far beyond nuclear physics, was very much Ray Herb's specialty and after retirement from the University (at age 65), Herb devoted his full time to the company he had created.

Ray Herb was an enthusiastic leader, a talent he showed at an early age, during his time at the Radiation Laboratory during World War II and again at Wisconsin. He was an inspiring teacher and was cited by Eugene Wigner in his Nobel address as one of the three great influences in his life. Many others would agree.

In 1945 Ray Herb married Anne Williamson, a daughter of a physics professor, and they raised five children (one of whom became a physicist). He was an outdoors man and lived in homes with beautiful views. As civilization encroached, he moved twice, ever further from Madison, but always to rustic locations. He enjoyed watching wildlife from his homes and hiking along trails in the woods behind his houses. He was an enthusiastic canoeist, often spending weekends in that pursuit. Even at age 85, when in Sweden to receive an honorary degree, he took part in a lengthy canoe trip with his wife, his physicist son, and his son's wife. He combined the desire for recreation with very hard work and up until a few days before he died he was active full time in his work.

defined the necessary characteristics of the stripping foil and showed how to bend particles 180 degrees so that the same accelerating column could be re-used, cheating nature. He dubbed the device a “Swindletron.” Nowadays such tandem machines are common.

I.6 Commercial Production of Electrostatic Machines

The specialized techniques needed to design modern accelerators are usually first developed in a large national laboratory or university department. Manufacturing industry is then asked to tender for the component parts a design with a rather precise specification, which the designers inspect during the manufacturing process. The result is that the manufacturers improve their expertise in certain fields of precision engineering, microwave technology or control systems and also their competitive technological position.

Logically the next step would be for the manufacturer to design and build complete accelerator systems, assuming the detailed design work and control of the manufacturing for itself. However, such are the technological leaps needed to keep pace with the growth in energy of accelerators for particle research that industry has no time to put to good use the techniques it has learned before it must learn more tricks to build a bigger and more advanced machine. The market for very large accelerators is also limited in number.

This was never the case in the manufacture of electrostatic machines; from early on specialist firms sold complete systems to many clients, and today industry offers complete cyclotrons for isotope production and hadron therapy as well as medium energy machines as synchrotron radiation sources on a turnkey basis.

In the case of electrostatic machines two companies were formed to produce accelerators on a commercial scale. One was the High Voltage Engineering Company (HVEC), formed in 1947 with John Trump as Chairman of the Board and Van de Graaff as Chief Scientist. The other was the National Electrostatics Corporation (NEC), formed in 1965 by Herb, J.A. Ferry and T. Pauly.

From 1947–1953 HVEC produced many generators operating up to 4 MV. These were both reliable and convenient. Building upon the experience developed at MIT, where a 12 MeV machine was constructed, the company went on to produce machines for as many as 15 different countries operating in the range from 6.0 MV to higher than 16 MV.

At the present time the company produces a large number of different electrostatic machines for a number of different purposes such as ion implantation, ion beam analysis of materials, accelerator mass spectroscopy, etc.

The National Electrostatic Corporation, started in 1965, had a difficult beginning, as the demand for nuclear instruments was limited and no one wanted to risk a large amount of money on a company with no track record. However, finally a 25 MeV Pelletron was sold to the University of Sao Paulo and, once this was seen to work, another to Oak Ridge. Many orders then came in and the company has to date produced 160 stable and reliable Pelletrons, located in 38 different countries. The company still specializes in these machines which can range from 25 MV down to 1 MV units for ion implantation.

I.7 Applications of Electrostatic Machines

Anyone working in a large high energy physics laboratory may be surprised to learn that although the frontiers of accelerator technology have moved away from devices that accelerate particles to a few MeV, the use of electrostatic accelerators is widespread and ever-increasing. There are literally thousands of them, which are applied to a wide range of scientific and industrial tasks, far beyond the conception of their inventors.

The original application was of course nuclear physics research and many Van de Graaffs and Pelletrons have been used for this purpose. The fact that their voltage may be very precisely controlled allows a detailed study of nuclear reactions and in particular narrow resonances in energy. Their advantage over other types of machines for such precise work may be judged by an anecdote from the World War II project to build an atomic bomb at Los Alamos. Precise values of neutron nuclear cross sections were needed to design the bomb and for this purpose a cyclotron from Harvard, a Cockcroft-Walton from the University of Illinois, and two electrostatic machines from the University of Wisconsin were secretly shipped to Los Alamos. The majority of the data that was needed came from the electrostatic machines.

Another interesting application is in the extensive study of the reactions that take place in stars — rather low energy by nuclear physics standards, and therefore requiring exacting work. In 1983 a Nobel Prize was awarded to William Fowler, of Caltech, for his “theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe” — experimental work that was all carried out on electrostatic machines.

Nowadays cyclotrons (Chapter II) and linear accelerators (Chapter III) are used in medicine rather than electrostatic accelerators, but perhaps the very first use of a nuclear machine in a hospital was in 1937 when Van de Graaff and John Trump constructed an electrostatic accelerator operating in the 0.5 to 1.2 MeV range. This was installed in the Harvard Medical School where it produced x-rays for cancer therapy.

In recent years electrostatic accelerators have been put to some unusual purposes. At the University of California in Santa Barbara, one was used as a driver for a Free Electron Laser (which is a powerful source of coherent radiation). Others have been used to generate the beam of electrons employed in electron cooling of ions, protons, and anti-protons where there is a need to have a “cold” (i.e., very mono-energetic and well-directed) electron beam moving along with exactly the same velocity as the heavy particles that are to be cooled. The heavy particles intermingle with the electrons and transfer some of their transverse motion to the electrons, thus becoming, themselves, more mono-energetic and better directed (“cooled”). Meanwhile the electrons are “heated” as they are deflected and excited but they are constantly replaced with fresh, cold electrons.

Another use of electrostatic accelerators is in a technique for material analysis called proton induced x-ray emission or PIXIE. In this technique protons are used to excite the atoms of the sample so that they emit x-rays. By analyzing the spectrum of the x-rays one may identify the chemical elements present in the sample. The proton beam can be made very narrow so that, for example, in environmental studies, one can excite one tree ring at a time. From the chemical composition it is then possible to map the atmospheric conditions year by year throughout the history of the tree. PIXIE has also been employed at the Louvre and other museums to detect art forgeries. In another study in Finland it was used to study trace elements in oyster shells as well as in old lead glass. It is also used to study trace elements in mineral exploration for locating regions where diamonds are likely to be found and has been widely used for biochemical and biological investigations.

Electrostatic accelerators are used to accelerate ions in the production of semiconductors. These are usually simple voltage columns; not complex machines. The ion beams are a tool to implant atoms into the interior of a semi-conducting wafer in order to alter its electronic properties. The energy needed to do this is small but must be controlled with precision to determine the depth at which the ions are deposited in a multi-layer circuit. This is the basis for the large industry of chips, which are at the heart of computers, cell phones, watches, mobile music devices, most consumer home products, and even automobiles.

Still another use of electrostatic accelerators, where again just the voltage column is used, is for accelerating the beam of an electron microscope. These devices employ the very short wavelength of electrons — quantum mechanics tells us that this wavelength is much shorter than that of light and therefore requires very high energy. In this way one may “see” smaller objects than one can with the naked eye or with normal optical microscopes. Modern electron microscopes can see individual atoms, and this is useful for many purposes, such as, for example, the design of efficient catalysts.

Electrostatic accelerators are very much a part of our modern life, and they can show up in surprising places, such as inspecting cargo passing through the Channel tunnel connecting England and France.

Far from being a museum exhibit, the electrostatic accelerator has thus found many applications in modern technology. Indeed the majority of the world’s accelerators are low energy electrostatic machines working away in industry or in chemistry, biology and materials science laboratories far removed from “big science.”