4 History of the Electrostatic Accelerator

J. McKay

Box 463, Deep River, Ontario, Canada K0J 1P0
mckay@magma.ca

4.1 Introduction

The history of electrostatic accelerators might be said to start with early experiments exploring electricity. The first electrostatic machines were constructed in the pursuit of sources of electric charge. Otto von Guericke [1] (1602–1686) may be credited as the inventor of the first electrostatic generator (1663), although he was more famous for his invention of the Magdeburg vacuum hemispheres used to demonstrate the strength of atmospheric pressure. The center of his electrostatic machine was a rotating sulfur sphere that achieved charge separation by friction. The charged ball was then used as a source of charge for experiments exploring the nature of electricity.

In 1784, Walckiers de St. Amand constructed a machine that used an endless band of silk passing over two wooden rollers. Cushions rubbed the silk belt to generate a charge. One version of this machine featured a silk belt 1.5 m wide and 7.6 m long [2]. Other friction machines of increasing complexity and ingenuity were invented throughout the eighteenth and early nineteenth centuries.

Designs that used induction to multiply charge replaced the early friction machines. James Wimshurst [3] built a new machine in about 1883 that was the culmination of these devices. Still manufactured today for use in schools and science displays, the Wimshurst machine was widely used in the late 1800s and early 1900s as a reliable source of high voltage for research.

To this point, electrostatic machines were used to explore the mysteries of electricity and as great parlour or popular lecture demonstrations. They often were beautiful and fantastic machines that appealed to the increasing curiosity of both the scientists and the public. References to and records of the devices are often fragmentary or indirect, making it difficult to give full credit to the many pioneers of the science of electrostatics.

A surprising number of features that became important in the later development of accelerators were considered in the development of these machines. St. Amand's silk belt foreshadowed Van de Graaff. In his graduation thesis (1872), Augusto Righi [4] (1850–1920) built a charge transfer device consisting of metal cylinders mounted on an insulated rope, quite similar in concept to Herb's Pelletron. Righi referred to his machine as a charge amplifier rather than a voltage generator, as it was used to amplify and measure very small electrical charges. It has been reported, in a reference given only as "an 1911 encyclopaedia", that F. Tudsbury, in 1900, discovered that an influence machine enclosed in a tank of compressed air or carbon dioxide would produce sparks more than double the length produced at atmospheric pressure. The inventors of this period showed great ingenuity as they built the first foundations of our knowledge of electrostatics. It is not surprising that many of their ideas were independently rediscovered as the technology of accelerators developed.

4.2 The First Accelerators

By the advent of the twentieth century, electrical phenomena were less mysterious, and practical sources of voltage and current became readily available. The interest in electrostatic machines waned. However, the fields of atomic and then nuclear physics began to develop. Spectroscopy and the search for ways to identify elements and ion species brought acceleration into use. In spectroscopy, ionized particles were accelerated across a constant voltage gap and then identified by their charge-to-mass ratio according to their deflection in a transverse magnetic field. Francis Aston (1877–1945), working in the laboratory of J.J. Thomson, invented the magnetic spectrometer and measured the ratio of neon isotopes [5]. The importance of this development is illustrated by the fact that Aston received the Nobel Prize for this work in 1922, just three year after his first measurements.

Ernest Rutherford (1871–1937), working in the Cavendish Laboratory at Cambridge in 1919, transmuted nitrogen atoms into oxygen by bombarding them with alpha particles from "Radium C", i.e. ^{214}Bi, which decays by a 0.02% branch to ^{210}Tl, producing a 5.617 MeV alpha particle [6]. This transmutation of nitrogen into oxygen was the first artificially induced nuclear reaction. In 1928, Rutherford, in an address to the Royal Society, identified the need for "a source of positive particles more energetic than those emitted from naturally radioactive substances". Low-energy positive ions were unable to penetrate the repulsive Coulomb barrier surrounding the positive nucleus of the atom. The need for accelerators had been established and the first era of accelerator development began.

J.D. Cockcroft (1897–1967) and E.T.S. Walton (1903–1995) obliged. In 1930, they accelerated protons to 200 keV, the first accelerated particle beam. Needing more energy, they devised and constructed a voltage multiplier circuit. In 1932, they accelerated protons to 600 keV and directed them onto a lithium target. The resulting $^{7}\mathrm{Li}(\mathrm{p},\alpha)^{4}\mathrm{He}$ reaction was the first accelerator-induced nuclear reaction [7].

The search for practical ways to accelerate ions was progressing on many fronts. Robert Van de Graaff (1901–1967) began experimenting with a belt-driven voltage generator at Princeton in the fall of 1929 and presented his concept at a meeting of the American Physical Society in 1931 [8]. He reported a voltage of 1.5 MV between the two spheres, one positive and one negative, of this device. Van de Graaff and his accelerator were transferred to the Department of Terrestrial Magnetism of the Carnegie Institution in Washington. A series of larger machines were built and tested, including one (with a 2 m sphere) that was too large to house indoors! These culminated, by late 1932, in a machine that accelerated protons to 600 keV. These were the first Van de Graaff beams used in a nuclear-physics experiment [9]. In October 1933, a new machine began operation at up to 1.2 MeV and a full nuclear-physics program commenced [10].

Electrostatic generators continued to grow in a most literal sense. Van de Graaff moved to the Massachusetts Institute of Technology in 1931 and began construction of the huge Round Hill double Van de Graaff in a former airship hangar. Two 4.6 m spheres topped a pair of 6.7 m tall Texolite columns. A maximum voltage differential of 5.87 MV was reached, and reliable operation at 5.1 MV differential was achieved [11]. No accelerator tube was installed in this generator. More modest machines, built in better-controlled environments, followed. A 2.75 MV accelerator using the positive Round Hill sphere produced useful beams for nuclear physics. Van de Graaff and John Trump published a paper [12] in 1937 describing a 1.2 MV electron accelerator built for the Harvard Medical School. This powerful source of 1 MeV X-rays was the first electrostatic accelerator used in clinical medicine.

At the same time that Van de Graaff and his associates were building large open-air machines, Ray Herb at the University of Wisconsin began experimentation with a series of enclosed machines. In 1931, after seeing the first primitive cyclotron at Ernest Lawrence's laboratory in Berkeley, Herb had worked with Glen Havens to build a vacuum-insulated belt-driven generator. This device achieved about 300 kV. In 1933, Herb decided to pressurize this 0.75 m diameter, 1.8 m long tank. At about 0.33 MPa air pressure, the generator reached 500 kV. Herb and his group immediately began development of a complete accelerator. In 1934, Herb was able to take data for his Ph.D. thesis. The developments that resulted in this successful accelerator were summarized in a 1935 paper in the Review of Scientific Instruments [13].

After completion of his doctorate, Herb spent some time at the Department of Terrestrial Magnetism in Washington working on the 1.2 MV open-air Van de Graaff type accelerator. Returning to Wisconsin in the fall of 1935, he, along with Parkinson and Kerst, developed a new 2.5 MV machine that incorporated many new features [14]. These included potential grading of the column and tube, a field-shaping column ring, feedback voltage control and an insulating gas mixture. This was contained in a 1.7 m diameter by 6.1 m long tank. The tube consisted of a series of metal electrodes separated by 6.4 cm long porcelain cylinders. The porcelain insulators had a corrugated profile. The tank was capable of withstanding a pressure of 0.75 MPa, twice that of the previous machine. While this machine was the first to have many of the attributes of a modern accelerator, it contained a lot of Texolite, red sealing wax and even some wood. At 0.75 MPa air pressure, the partial pressure of oxygen posed a major hazard. After a number of fires, a permanent CO_2 injection system was installed.

In 1939, this 2.5 MV machine was disassembled and the tank was used to contain a new accelerator. The new machine had a tube almost 4 m long, two potential-grading "intershields" and a single-ended configuration for the column [15]. This highly successful accelerator ran reliably at 4.3 MV and held the record for the highest voltage until the early 1950s.

External events had major effects on the development of accelerators in the period between World Wars I and II. The crash of 1929 and the start of the Great Depression coincided with the first development of accelerators. The next ten years saw a great deal of progress, but budgets were very tight and a premium was placed on sealing wax and ingenuity.

4.3 The Postwar Years

The Second World War changed the face of science. The Herculean efforts of the Manhattan Project, as well as producing the atomic bomb, had the secondary effects of vastly increased knowledge in physics and technology. Peace brought expectations of large research budgets and the hope of limitless progress. This set the stage for the next major period of progress in electrostatic accelerators.

Herb's 4.3 MV machine had run almost constantly at Los Alamos, complemented by a 2.0 MV machine built by Joe McKibben, another Wisconsin graduate. At MIT, Van de Graaff and his associates designed a vertical 4.0 MV machine that introduced resistor grading to the column and tube structure. This machine was replicated at Chalk River and at other laboratories. 1947 marked the establishment of the High Voltage Engineering Corporation by Trump, Denis Robinson and Van de Graaff and soon began supplying electrostatic generators used in cancer therapy and radiography and in studies of nuclear structure. One of their first products, produced with Ray Herb as a consultant, was a 4 MV electrostatic accelerator required as the injector for the "Cosmotron", the first proton synchrotron. This combination came on line in 1952. The injector was still running, but for other purposes, in 1999 [16].

In the late 1940s, Trump [17] at MIT and McKibben [18] at Los Alamos constructed new machines with the aim of reaching 12 MV. The Los Alamos machine reached 13 to 14 MV without tubes, but both machines were limited to 8–9 MV in practical operation. These large machines doubled the useful energy achieved by Herb's prewar machine. The MIT design was used by HVEC as a prototype for its CN series of accelerators. Twenty-six CNs were installed between 1951 and 1966, the first "mass-produced" accelerators. In the same period, HVEC produced many 3 and 4 MV KN series machines, as both electron and positive-ion accelerators.

These commercially produced accelerators had many common features: resistor grading of the column and tube, PVC-sealed glass and metal tubes, belt charging, field-shaping column hoops and high-pressure (0.7 to 0.8 MPa) N_2 plus CO_2 gas insulation.

The single-ended machines provided practical beams for the growth of nuclear-structure studies but it was clear that much higher energies would be required to explore the vast expanse of the table of isotopes. Voltages on the order of 10 MV were achievable, but tube and column structure limitations inhibited progress above that level. Size could accomplish only so much, and cost and complexity expanded at a higher rate than voltage.

4.4 Tandems

In the 1930s, a number of researchers experimented with charge exchange schemes of acceleration. Otto Peter at the University of Geiszen used multiple stages of positive- and negative-hydrogen acceleration to produce a 100 pA beam [19]. Independently, W.H. Bennett (1903–1987) suggested and later patented [20] the concept of an energy-doubling accelerator. The practical application of these ideas would wait until the mid 1950s and the development of a sufficiently intense source of negative protons. Publications by Luis Alvarez [21] in 1951 and Bennett [22] in 1953 refined the tandem concept. A.C. Whittier at Chalk River measured in 1954 the cross sections for negative-hydrogen-ion production in various gases at various energies [23]. Weinman and Cameron produced a 20 μA beam of H^- at Wisconsin [24] in 1956.

This activity induced the Chalk River Nuclear Laboratory (CRNL), in 1954, to invite HVEC to submit a proposal for a 5 MV tandem. Thus began a period of explosive advance in accelerator technology. September 1956 saw the placing of an order from CRNL to HVEC for the first tandem accelerator. The first test experiments with beams from the tandem were performed at HVEC in Burlington, Massachusetts, on 25 June 1958. The machine was moved north to Chalk River, and the first beam on target was achieved there in February the next year.

The "EN" tandem, as it was designated, had a glass and steel, epoxy-bonded, horizontal column and a single belt. The tank was 2.4 m in diameter and 11 m long. Rated at 5 MV, it ultimately ran as high as 7 MV. This machine was moved to the Université de Montréal in the late 1960s, where it continues to run and has recently been upgraded. EN-1 was the prototype for 30 similar machines produced between 1958 and 1973.

As exciting as the development of the EN was, it was supplemented by a similar but larger machine, the "FN", first delivered to Los Alamos in 1963. This accelerator was 3.66 m in diameter and 13.4 m long. Rated at a nominal

7 MV, FN accelerators have been known to run relatively reliably at over 11 MV. Nineteen FN accelerators were manufactured.

The next step in HVEC's series of machines was the "MP" model. MP-1 was delivered to Yale University in 1965. This machine represented a major advance in design only six years from the delivery of the first tandem. The simple compressed column was replaced with a truss bridge structure, still glass and steel, still compressed, but twice the length of that of the first tandems. The tank of the MP was over 20 m long and over 4.5 m in diameter. The earliest years of MP operation were beset with many problems as operators learned how to control it. In a few instances, some FNs were operating embarrassingly at the same voltage as the larger and much more expensive machines. The MPs eventually were refined and ran at voltages far above their nominal 10 MV rating. Michel Letournel and his colleagues at Strasbourg ultimately pushed a modified MP to 18 MV with beam [25].

In a period of just 14 years, from the installation of EN-1 in 1959 at Chalk River to the installation of MP-10 at Strasbourg in 1973, HVEC produced 55 tandem accelerators. The MP was the last of the "mass-produced" large tandems.

The advances made by these HVEC machines were made possible by a number of innovations. The inclined field tube design by Van de Graaff, Rose and Wittkower [26] in 1962 greatly reduced the limitations imposed by earlier tube designs. The continued development of better resistors helped to control voltage-gradient variations. The introduction of SF_6 insulating gas, either 100% or as a mixture, extended the voltage range. Improvements in ion sources provided critical advances in beam variety and intensity. Adaptation of Herb's Pelletron charging systems to replace the belt in HVEC machines brought further advances in reliability and performance. Second stripping of ions in the high-energy column produced higher charge states of heavy ions and therefore higher beam energies.

In parallel with the development of the commercially available HVEC machines, there was the construction of other designs. Two 5 MV vertical tandems were built in 1959 by the Metropolitan-Vickers Electrical Company in the UK for the Harwell and Aldermaston Laboratories [27]. In 1965, the Japanese government ordered two 5 MV machines: a vertical tandem from Toshiba that was installed at the University of Tokyo [28] and a horizontal machine by Mitsubishi installed at the University of Kyoto.

A new commercial supplier was founded in 1965 with the formation of the National Electrostatics Corporation (NEC) by Herb, James Ferry and Theodore Pauly. Since his return to the University of Wisconsin in 1946, Herb had directed an extensive program of research into vacuum techniques, ceramic-to-metal bonding, charging systems and other accelerator technologies. This was in addition to his extensive research in nuclear physics. The company's first accelerator order was for a coupled system combining a 4 MV single-ended machine injecting into an 8 MV tandem. These machines were shipped to São Paulo, Brazil, in November 1970, and in December, NEC received an order from the Australian National University for a 14 MV vertical tandem. The ANU machine was reported to be running at 16.7 MV in 1988 [29]. The ultimate challenge came in 1975 with an order from the Oak Ridge National Laboratory for a 25 MV tandem. The first NEC machines represented a huge risk for the new company and a radical departure from the HVEC designs. The machines were vertical. They featured a modular construction, ceramic insulators, corona point gradient control, high-vacuum ceramic tubes and the new "Pelletron" charging system. This system of linked metal cylinders and insulated sections was devised by James Ferry during the years of work by the University of Wisconsin group. The successful design followed early antecedents such as Righi's 1872 charge amplifier and many unsatisfactory prototypes until a workable design evolved.

Between 1970 and 1991, NEC manufactured 11 large tandems. In addition to those mentioned above, "14UD" tandems were supplied to the Weizmann Institute in Israel and the Tata Institute in India. 20 MV tandems were built for the Japan Atomic Energy Research Institute (JAERI) and for the Comisión Nacional de Energia Atómica in Buenos Aires, Argentina. A 15UD went to the Nuclear Science Centre in New Delhi, India, in 1991.

The NEC era was marked by a switch to vertical machines and heroic design leaps. The 14 and 15 MV machines were "straight-through" tandems, and the others were "up–down" or "folded", that is, the beam was deflected 180° in the terminal and returned to ground. There was no production of large series of similar machines, but the NEC modular approach to construction mitigated this to a large extent.

The major production era for the HVEC tandems spanned 1959 to about 1973, and the NEC era spanned 1970 to 1991. Production of large tandems by the two great commercial producers barely overlapped.

4.5 The Big Machines

Efforts to push beyond the 20 MV level began in the early 1970s as the great era of tandem expansion slowed. A number of unique machines were the result. Three were extensions of the standard MP design and three were very large, unique machines.

A modified MP-style accelerator called the XTU was supplied by HVEC to the Laboratori Nazionali di Legnaro, Padova, Italy. Based on the MP structure in an enlarged tank and equipped with a Laddertron charging system, the XTU was designed to inject into a linac booster at 15 MV. This machine was accepted in 1981 and went into full operation in 1984. Commissioning of the ALPI booster started in 1994.

Components of MP-0, the HVEC test machine, were recycled into the HI-13 Beijing accelerator that saw first beam in 1985. The HI-13 features an enlarged tank and a Laddertron charging system. It runs in the 13 MV range.

In 1972, the Science Research Council in Britain approved the development and construction of a 30 MV tandem to be built at Daresbury. The design team came from neither the HVEC nor the NEC tradition and they resolved to make electrostatic design more scientific and less empirical. The history of the project was summarized by T.W. Aitken at the Padova conference in 1992 [30]. Aspects of field distribution, inductive charging systems, breakdown of SF_6 in spark gaps, surge protection of electronics, organic-free tubes, control systems and many more items were studied and tested in detail. Commissioning of the resulting machine began in 1980. It was a "straight-through" tandem with an active tube length of 18 m in each column. The charging system, later marketed by HVEC as the "Laddertron", consisted of pairs of cylinders interconnected by flat sections reminiscent of the rungs of a ladder. This charging system is used at Stony Brook in an FN, as well as in the Orsay, Beijing and Legnaro accelerators. The tubes were of brazed ceramic–metal construction. The internal electronics were controlled over infrared light links. This great machine reached 29.5 MV during voltage testing but was unable to exceed about 20 MV in full operation [31]. When the facility was shut down in 1992, tube improvements were being considered that could have taken it to a higher operating range.

The Oak Ridge National Laboratory, in 1975, ordered a 25 MV tandem from NEC. Unlike the Daresbury machine, this tandem was built in the "folded" configuration with a large 180° magnet in the terminal. The 25URC Oak Ridge machine was tested, in 1979, at 32 ± 1.5 MV without tubes [16]. This stands as the current record for the maximum voltage produced with any machine. However, like Daresbury, it originally had difficulty running at over 20 MV. Today, it runs at almost 24 MV with beam.

Construction of the "VIVITRON" [32], based on Letournel's experiments on the Strasbourg MP, began in 1985 and achieved first beam in 1993. The tank was 50 m long but only 8.4 m in diameter at the center. A series of seven "porticos", or open cages, surrounded the column to control the radial gradient. The assembly was supported with insulating posts, and the column was made up of large plastic plates. A charging belt ran through the full length of the machine. Development of this radical design of this machine produced a greater understanding of electrostatic design. However, a variety of problems inhibited operation over 20 MV. The VIVITRON was shut down in December 2003.

The last of the big machines to be built was the ESTU accelerator at Yale University [33]. This project extended the active structure of MP-1 by 25%, and incorporated a single Letournel "portico" and a 7.6 m diameter tank with a shape optimized for the portico. More modest in its aim than the 25URC or the VIVITRON, the ESTU structure was tested to about 22.5 MV in 1987 and runs consistently in the 19 MV range. This machine is a true hybrid, combining a structure and tubes from HVEC with a charging system from

NEC and resistors and a portico structure from Vivirad, a company founded by Michel Letournel.

The great machine at Oak Ridge is at the pinnacle of electrostatic-accelerator development to date. Successfully running at 24 MV [34], the Oak Ridge machine is now accelerating radioactive beams as its primary role. It was planned to, and did, inject particles into the ORIC cyclotron for boosting its energy. Now that cyclotron is being used to generate radioactive ion species for injection into the tandem. Such versatility is the hallmark of many electrostatic-accelerator laboratories.

In his 1974 review paper [35], Allan Bromley stated, "Looking further into the future, electrostatic accelerator technology has now advanced to the point where it becomes reasonable to at least consider designs for tandem electrostatic accelerators in the 50–60 MV range". This prediction reflected the optimistic view of many in the field of electrostatics at that time. It was also a period of generous funding fueled by the advances in nuclear-structure research. The explosion of ideas in this field called for ever-greater energies in order to breach the Coulomb barrier in the heaviest nuclear systems.

As the voltage increases, electrostatic accelerators suffer from the fact that the stored energy in a capacitive system increases as the square of the voltage. Further, the capacitance increases as the accelerator gets larger. Thus spectacular sparks in the 20 MV plus range often lead to serious damage in large accelerators.

The difficulties in achieving higher voltages led to the adoption of more complex "afterburner" schemes, where the tandem injected a beam into a linac or cyclotron for final acceleration. This raised the question of whether the tandem was the main accelerator or just a large ion source!

Booster accelerators were being planned in the mid 1970s even though the suggested technologies, such as superconducting linacs or cyclotrons, were very complex. The Chalk River superconducting-cyclotron concept was described at conferences in 1974, but it was not operational until the late 1980s. The superconducting linacs came on line sooner, usually with just a few modules to start. Injection of beam from the Oak Ridge 24URC into the ORIC cyclotron, built in the 1960s, was planned from the start of the project and was achieved in 1982 [36].

Of the four super machines, Daresbury, Oak Ridge, the VIVITRON and Yale, only Oak Ridge and Yale remain in operation in 2004. Five of the eleven MPs have been taken out of service. About 75% of the smaller, first-generation tandems are still in operation, although many have been moved to new institutions. Their versatility and relatively low cost of operation have preserved them. Many have been converted to Pelletron charging and otherwise upgraded. Amongst other useful roles, these machines often serve as test beds for new ion beam application technologies and applications, helping to define the requirements for the next generation of machines.

4.6 Machines for Applications

The emphasis in histories of electrostatic accelerators is on the ever-larger machines built for research in nuclear physics. However, the vast number of accelerators are smaller, low-voltage machines used in a wide variety of applications. The commercial suppliers" survival and prosperity is based on these small machines. The wide variety of charging systems divides these smaller potential-drop accelerators into the classifications of electrostatic accelerators, with mechanical (i.e. belt or chain) charging, and cascade accelerators, including asymmetrical, symmetrical and parallel-driven circuits, insulating-core transformers, etc. The line between a high-voltage electrostatic generator and a power supply has become blurred.

Most accelerators in the world are used as implanters or for accelerator mass spectrometry (AMS), materials research, biology or medical applications. Many of these applications are discussed in Part III of this book. The main interest of the users is in the application of the machine rather than in the machine technology. Whereas the research community could risk some unreliability in the quest for elusive results, the applied users see the accelerator almost as an appliance and expect beam on demand. The manufacturers have been able to fill this need to a large extent, and it is not unusual to find users reporting that they have not had to open their accelerators for service in a year or more. It is interesting to note that tandem machines for applications are now up to 5 MV, the same rating as the first tandem in 1957. There has also been a resurgence of cascade-type machines in the development of more stable and reliable accelerators for applications.

4.7 The Future

The current state of development of electrostatic accelerators poses the question of whether we shall see construction of another large machine. High energies can be obtained from postaccelerator systems and, at the other extreme, astrophysicists seek intense low-energy beams. Fields such as AMS look for beams of great stability and purity. Industrial and medical applications require high reliability and ease of operation.

The changing demands of science and the availability of high-energy beams from booster systems have dulled the quest for higher voltages. That, combined with the technical and financial challenges involved in attaining significantly higher voltages, makes it doubtful that we shall see development of new large machines in the near future.

In the 75 years since Rutherford called for "a source of positive particles more energetic than those emitted from naturally radioactive substances", we have seen periods both of rapid development and of consolidation. Nuclear-structure physics was the dominant driving force for accelerators in the 1960s and 1970s. Slowly, lower-voltage machines started to find uses in applications of the techniques of nuclear physics. Material analysis and modification, particularly in the manufacture of solid-state devices, became important. AMS pushed analysis techniques to spectacular sensitivities and forced accelerator developers to new understandings of machine operation and the need for ultrastable operation. Part III of this volume discusses the uses of accelerators, and only two of the ten chapters deal with nuclear physics. In 2004, it is the needs of applications that now drive the development of electrostatic accelerators.

A number of review papers have been written over the years describing the development of the electrostatic accelerator [16, 35, 37, 38]. International conference series, such as the Heavy Ion Accelerator Technology Conferences that began in Daresbury in 1973, have chronicled progress in the field. The Symposium of North Eastern Accelerator Personnel started in 1968 and has met annually to discuss the problems in the operation of electrostatic accelerators. These meetings highlight the collaborative efforts of the community and the importance of contributions by a great number of both researchers and operations people in the field.

This chapter relates only a small portion of the countless contributions made to the science of electrostatics. The exchange of ideas through the years and the accumulation of experience by the practitioners of the art and science of electrostatics form a rich story indeed.

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