Maxwell, Hertz, and German Radio-Wave History

ADOLF J. SCHWAB, FELLOW, IEEE, AND PETER FISCHER, MEMBER, IEEE

Although early reports about electricity and magnetism date back before Christ, it took another 2000 years until in the eighteenth century, men like B. Franklin, A. Volta, C. Coulomb, L. Galvani, and many others studied more intensely electrostatic and magnetostatic effects. In contrast to mechanics, hydrodynamics, and astronomy, which belonged to the mathematics discipline, electricity and magnetism were usually investigated by physicians, pharmacists, priests, philosophers, chemists, and fascinated amateurs. However, at the end of the eighteenth century and the beginning of the nineteenth century, researchers with mathematical background took over in France and later in Great Britain and Germany. Because of the many schools of thought and parallel developments in the nineteenth century, it is appropriate to first mention the many evolutionary achievements made outside Germany and then consider German contributions.

Keywords— *Hertz's experiments, Lorentz gauge, Maxwell's theory.*

I. ACHIEVEMENTS OUTSIDE GERMANY

The basic ingredients of radio waves, electric and magnetic fields, have their roots in observations made by *Oerstedt, Ampere, Faraday,* and *Maxwell* in the decades 1820–1870 [1]. Oerstedt (Denmark) discovered in 1820 that flowing electricity, nowadays designated as *current,* exerted forces on metal. This was a major milestone because previous experiments had dealt only with electrostatics of charged bodies or voltages from electrochemical batteries. Moreover, Oerstedt stressed the importance of a *closed circuit* in order that electricity could *flow* and discovered the *circular* nature of magnetism caused by flowing electricity. Upon his discoveries, research of electricity and magnetism attained a new quality. Previously, electricity and magnetism were considered isolated phenomena; now, attention was payed to their interrelationship. Ampere followed up Oerstedt's findings in the very same year, discovered mutual forces between current-carrying conductors, delivered an equation permitting the calculation of the forces between the conductors, and postulated *circular currents* as unique sources of all manifestations of magnetism.

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The authors are with the Institute of Electric Energy Systems and High-Voltage Technology, University of Karlsruhe, Karlsruhe D-76128 Germany (e-mail: a.schwab@ieee.org).

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With their experiments, Oerstedt and Ampere had shown that electricity could be transformed into magnetism. In 1831, Faraday demonstrated the reverse phenomenon and showed that magnetism could as well be transformed into electricity. He had, in other words, discovered the phenomenon of *induction* [1], [2]. Moreover, he coined the concepts of *lines of force, dielectrics,* and, eventually, *fields* (1845). He even suggested an interpretation of light as *undulations* of his lines of force.

For most of Faraday's contemporaries, nature consisted of discrete particles that, in analogy to Newton's gravitational law, exerted instantaneous attracting or repelling forces upon each other over large distances, the so-called theory of action at a distance. Its foremost protagonists were Ampere, *Neumann,* and *W. Weber*. In contrast, Faraday interpreted nature to be macroscopically continuous, and forces on a body brought into the environment of conductors or poles would be related to local quantities at that body's location (theory of *local action*). He claimed that his lines of force represented *continuous fields* and, in addition to that, could be *curved,* which strongly opposed the widely accepted *Newtonian-mechanics*-based approach with its *straight* lines of force.

One of the *few* contemporaries who supported Faraday's field concept was Maxwell (Fig. 1), who in 1862 published an article "On Physical Lines of Force." His subsequent thoughts were published in 1865 in his article "A Dynamical Theory of the Electromagnetic Field." Maxwell brought existing equations and his own genuine concepts together and composed a consistent set of equations [2]. Hertz (Fig. 2), who felt great admiration for Maxwell, stated: "The theory of Maxwell is best defined as the System of Maxwell's Equations."

The most outstanding innovative feature of Maxwell's mathematical models of electric and magnetic fields was the concept of *displacement current* $\boldsymbol{J}_d = \partial \boldsymbol{D}/\partial t$, which allowed for the continuity of current flow also in *open* circuits, in other words, in nonconducting media. As a consequence of that, his displacement current allowed the derivation of wave equations for electric and magnetic fields, formally identical with wave equations known from continuum mechanics. These equations suggested the ex-

Fig. 1. J. C. Maxwell.

Fig. 2. H. Hertz.

istence of electromagnetic waves. According to Maxwell's theory, each time-varying electric field $\boldsymbol{E}$ was related to a magnetic field $\boldsymbol{H}$, for instance, in *free space*

$$\mathrm{curl}\,\boldsymbol{H} = -\varepsilon_0\, d\boldsymbol{E}/dt \tag{1}$$

and each time-varying magnetic field $\boldsymbol{H}$ was related by induction to an electric field $\boldsymbol{E}$

$$\mathrm{curl}\,\boldsymbol{E} = -\mu_0\, d\boldsymbol{H}/dt. \tag{2}$$

The coupled fields $\boldsymbol{E}$ and $\boldsymbol{H}$ would propagate in the form of electromagnetic waves with the finite velocity of light.

This was in strong contradiction to the theory of instantaneous action at a distance. According to Oerstedt and Ampere, magnetic fields existed only in the vicinity of permanent magnets or currents flowing in *closed* circuits. *Maxwell's* equations could also cope with *open* circuits. Moreover, his waves could transport energy monodirectionally away from the site of their generation. It is not surprising that his theory was strongly questioned by many contemporary scientists. Though he had strong early supporters—for instance, *Fitzgerald, Poynting, Heaviside, Thomson,* and *Larmor,* so-called *Maxwellians*—his concept of displacement current became widely accepted only upon the experimental proof of the existence of electromagnetic waves by Hertz in 1888.

The original system of Maxwell's equations was written in terms of *potentials* with Cartesian coordinates and, therefore, was difficult to digest even for involved physicists. Therefore, Heavyside and Hertz rewrote Maxwell's equations in terms of field quantities, and Lorentz added vector notation [4]. This led to Maxwell's equations in differential form as we use them today

$$\mathrm{curl}\,\boldsymbol{H} = \boldsymbol{J}_c + \frac{\partial \boldsymbol{D}}{\partial t} = \boldsymbol{J}_c + \boldsymbol{J}_d \quad \mathrm{curl}\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$
$$\mathrm{div}\,\boldsymbol{B} = 0 \quad \mathrm{div}\,\boldsymbol{D} = \rho. \tag{3}$$

This system of equations, which applies to continua only, was later augmented by Hertz and Lorentz in order to consider also the granular, atomistic structure of matter possibly existing in the field domain. These *Maxwell–Lorentz* equations [3] are given by

$$\mathrm{curl}\,\boldsymbol{H} = \boldsymbol{J}_c + \frac{\partial \boldsymbol{D}}{\partial t} + \mathrm{curl}\,\boldsymbol{M} + \frac{\partial \boldsymbol{P}}{\partial t} \quad \mathrm{curl}\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$
$$\mathrm{div}\,\boldsymbol{B} = 0 \quad \mathrm{div}\,\boldsymbol{D} = \rho - \mathrm{div}\,\boldsymbol{P} \tag{4}$$

where $\boldsymbol{P}$ is the *polarization* of dielectric and $\boldsymbol{M}$ the *magnetization* of magnetic matter, respectively. With the systems of (3) and (4), Maxwell had crafted the essential theoretical foundations for today's "radio waves."

II. Electrodynamics in Germany

German electrodynamics in the early nineteenth century were influenced by the French mathematical tradition represented by scientists like *Poisson, Laplace, Fourier, Legendre,* etc. Instead of investigating and understanding electrodynamics experimentally, many physicists, supported by mathematicians, strived increasingly for mathematical equations or formulas. *Ohm* was the first to apply the new paradigm (1827). Because of the contemporary belief that voltages and currents were isolated phenomena and because of his "mathematical approach," it took more than ten years until his law became generally accepted.

Theoretical physics with electrodynamics competence existed at the Universities of *Königsberg, Göttingen,* and *Berlin* [5].

- Königsberg is considered the major root of theoretical physics in Germany, mainly due to F. Neumann (1798–1894). He and his students, amongst them

Kirchhoff, spread theoretical physics all over Germany. Other famous names were *Jacobi, Minkowski, Wien, Wiechert, Hilbert,* and *Bessel.*

- In Göttingen were *Gauss, Dirichlet* (formerly in Berlin), *Riemann, Clausius,* and *Weber.*
- In Berlin were *Helmholtz,* Kirchhoff, and their student Hertz, who later made his famous discoveries at the University of Karlsruhe.

In 1835, Gauss dealt with fundamental electromagnetic laws. Based on Ampere's law, he derived an equation for the forces between current-carrying conductors that considered the relative velocity between charges in motion. Maxwell said about Gauss:

> Gauss, a member of the German magnetic union, brought his powerful intellect to bear on the theory of magnetism, and on the methods of observing it, and he not only added greatly to our knowledge of the theory of attractions, but reconstructed the whole of magnetic science as regards the instruments used, the methods of observation, and the calculation of the results, so that his "Memories on Terrestrial Magnetism" may be taken as models of physical research by all those who are engaged in the measurement of any of the forces in nature.

Nevertheless, Gauss declined to publish his thoughts on electromagnetics at that time because he was "missing the *keystone* which would consider appropriately the noninstantaneous effects of electricity" (italics added).

In 1845, Neumann presented his mathematical law of induction derived from *potentials.* The potential concept had evolved from mechanics [Lagrange (1773) and Laplace (1782)] and had first been used in the context of electrostatics by Poisson. One year later, Weber, who was a friend of Gauss', presented his "Fundamental Law of Electrodynamics," describing the force between charges at rest and in motion

$$\boldsymbol{F} = \frac{ee'}{\boldsymbol{r}^2}\left(1 - \frac{1}{2c^2}\left(\frac{dr}{dt}\right)^2 - \frac{2r}{c^2}\,\frac{d^2r}{dt^2}\right) \tag{5}$$

with e, e' a pair of charges, c the velocity of light, dr/dt the *relative* velocity of e, e', and d^2r/dt^2 their acceleration. This law was a formal analog to Newton's gravitational law (inverse square law) augmented by two terms considering charges in motion. All force components were assumed to act everywhere instantaneously, no matter what the distance would be, and attracting as well as repelling forces acted along straight lines. For bodies at rest, this law simplified to Coulomb's law. Weber's law yielded correct results for closed circuits and static or quasistatic processes; therefore, it was widely accepted. It implied instantaneous action at a distance, however, which was controversial. In contrast to Maxwell's theory, it could handle neither open circuits nor unstationary processes.

The deficiencies of the theory of action at a distance could be partly overcome by retarded potentials introduced in 1858 by Riemann [6], *C. Neuman* (F. Neumann's son), and later by Lorenz [4]. Retarded potentials relate instantaneous effects at a given field point in space to the charge distribution $\rho(\boldsymbol{r}, t)$ and current density distribution $\boldsymbol{J}_c(\boldsymbol{r}, t)$ in a source point at a time diminished by the traveling time $t_t = (r/a)$ between the source and the field point, respectively

$$\varphi_{\text{ret}} = \int_{V_q} \frac{\rho\left[r_q, \left(t - \dfrac{|\boldsymbol{r} - \boldsymbol{r}_q|}{v}\right)\right]}{4\pi\varepsilon|\boldsymbol{r} - \boldsymbol{r}_q|}\, dV_q$$

$$A_{\text{ret}} = \int_{V_q} \frac{\mu \boldsymbol{J}_L\left[\boldsymbol{r}_q, \left(t - \dfrac{|\boldsymbol{r} - \boldsymbol{r}_q|}{v}\right)\right]}{4\pi|\boldsymbol{r} - \boldsymbol{r}_q|}\, dV_q. \tag{6}$$

Substituting these retarded potentials for φ and $\boldsymbol{A}$ in

$$\boldsymbol{E} = -\text{grad}\,\varphi - \frac{\partial \boldsymbol{A}}{\partial t} \tag{7a}$$

and

$$\boldsymbol{H} = \frac{1}{\mu}\,\text{curl}\,\boldsymbol{A} \tag{7b}$$

yielded for closed circuits the same solutions for $\boldsymbol{E}$ and $\boldsymbol{H}$ as Maxwell's theory.

The potentials (6) were solutions of wave equations

$$\Delta\varphi - \mu\varepsilon\frac{\partial^2\varphi}{\partial^2 t} = -\rho/\varepsilon \tag{8a}$$

and

$$\Delta\boldsymbol{A} - \mu\varepsilon\frac{\partial^2\boldsymbol{A}}{\partial t} = -\mu\boldsymbol{J}_c. \tag{8b}$$

Because these equations had been obtained employing an artifice nowadays called a Lorentz gauge, φ and $\boldsymbol{A}$ in (8a) and (8b) possessed a different meaning as compared with the classical concepts. Hence, they must be indexed, for example, by L

$$\Delta\varphi_L - \mu\varepsilon\frac{\partial^2\varphi_L}{\partial t^2} = -\rho/\varepsilon \tag{9a}$$

and

$$\Delta\boldsymbol{A}_L - \mu\varepsilon\frac{\partial^2\boldsymbol{A}_L}{\partial t^2} = \mu\boldsymbol{J}_c. \tag{9b}$$

Most important, $\boldsymbol{A}_L$ in (9b) consists of a rotational component $\boldsymbol{A}_{L_{\text{rot}}}$ and an irrotational component $\boldsymbol{A}_{L_{\text{irr}}}$ hence, div $\boldsymbol{A} \neq 0$.

Retarded potentials were not based on the existence of a displacement current, a concept that at that time did not even exist.

Further, because the magnetic vector potential $\boldsymbol{A}_L$ in (9b) had an irrotational component, (7a) had to be decomposed into

$$\boldsymbol{E} = \underbrace{-\text{grad}\ \varphi_L - \frac{\partial \boldsymbol{A}_{L_{\text{irr}}}}{\partial t}}_{\boldsymbol{E}_{\text{irr}}} - \underbrace{\frac{\partial \boldsymbol{A}_{L_{\text{rot}}}}{\partial t}}_{\boldsymbol{E}_{\text{rot}}}. \qquad (10)$$

Basically, Maxwell appreciated Weber's and his colleagues' scientific work:

> Great progress has been made in electrical science, directly in Germany, by cultivators of the theory of action-at-a-distance. The valuable electrical measurements of W. Weber are interpreted by him according to this theory, and the electromagnetic speculation which was originated by Gauss, and carried on by Weber, Riemann, J. and C. Neumann, Lorenz, etc., is founded on the theory of action-at-a-distance, but depending either directly on the relative velocity of the particles, or on the gradual propagation of something, whether potential or force, from the one particle to the other. The great success which these eminent men have attained in the application of mathematics to electrical phenomena, gives, as is natural, additional weight to their theoretical speculations, so that those who, as students of electricity, turn to them as the greatest authorities in mathematical electricity, would probably imbibe, along with their mathematical methods, their physical hypotheses.

Nevertheless, Maxwell spoke out very clearly when advocating for his own approach:

> These physical hypotheses (action-at-a-distance), however, are entirely alien from the way of looking at things which I adopt, and one object which I have in view is that some of those who wish to study electricity may, by reading this treatise, come to see that there is another way of treating the subject, which is no less fitted to explain the phenomena, and which, though in some parts it may appear less definite, corresponds, as I think, more faithfully with our actual knowledge, both in what it affirms and in what it leaves undecided. In a philosophical point of view, moreover, it is exceedingly important that two methods should be compared, both of which have succeeded in explaining the principal electromagnetic phenomena, and both of which have attempted to explain the propagation of light as an electromagnetic phenomenon and have actually calculated its velocity, while at the same time the fundamental conceptions of what actually takes place, as well as most of the secondary conceptions of the quantities concerned, are radically different.

Further, he said, "I have no doubt that the method which I have called the German method will also find its supporters and will be expounded with a skill worthy its ingenuity."

Helmholtz did not fully appreciate Weber's law. He wrote a series of three articles in which he questioned its generality and presented his own generalized induction law, including a parameter $K(+1, -1, 0)$, depending on which his general law reduced to Neumann's, Weber's, or Maxwell's theory. To obtain more support for Maxwell's theory, Helmholtz proposed to the Academy of Berlin the creation of a prize for its experimental proof. Helmholtz's graduate student Hertz knew immediately that the state-of-the-art apparatus would not permit that proof and, therefore, did not spend much time in making an attempt. He completed his doctorate degree on the "Induction of Rotating Spheres" in Berlin (1880) and became a lecturer in Kiel, where he investigated gas discharges. Eventually, he became a full professor at the University of Karlsruhe (1884), where he made his famous discovery of the existence of real electromagnetic waves (Fig. 3).

In 1886, 22 years after Maxwell's publication, while discharging a Leyden bottle via a large inductor, Hertz observed at remote corners of his laboratory secondary sparks that could not be explained by the classical induction law. He inferred that his discharge was of oscillatory nature with a frequency of approximately 80 MHz. This frequency had allowed radiation of energy in the form of an electromagnetic wave as predicted by Maxwell. He reported his findings to the Academy of Berlin in 1887 and won the Berlin Prize (Fig. 4).

In his subsequent systematic experiments, he proved that electromagnetic waves propagated indeed with the speed of light and that electromagnetic waves regarding, reflection, diffraction, and polarization possessed the same properties as light.

By positioning the conductor in which the oscillations were generated in the focal line of a parabolic mirror, Hertz could even generate a radio-frequency beam that could be oriented in arbitrary directions. This was the breakthrough for the broad acceptance of Maxwell's theory on the continent.

Maxwell, from his careful mathematical deductions, had postulated the existence of electromagnetic waves, and Hertz had experimentally verified Maxwell's hypothesis. The coupled electric and magnetic fields of electromagnetic waves (Fig. 4) were indeed "light" with large wavelengths in an invisible frequency region.

Hertz said: "The results are fatal to any and every theory which assumes that electric force acts across space independent of time. They mark a brilliant victory for Maxwell's theory." With his findings, Hertz had decided the controversy between *action at a distance* and *local action* in favor of Faraday and Maxwell.

In 1888, Hertz became a full professor in Bonn, succeeding Clausius. He spent his time modifying Maxwell's system of equations into a form more easily digestible for the ordinary physicist and investigated the electrodynamics of moving bodies, a first step toward the theory of relativity. Although Hertz is preferably known for his experimental proof of Maxwell's theory, he has dealt with many other domains of physics such as mechanics, cathode rays, gas discharges, the effect of ultraviolet light on sparks (photoelectric effect), etc. Unfortunately, Hertz passed away at

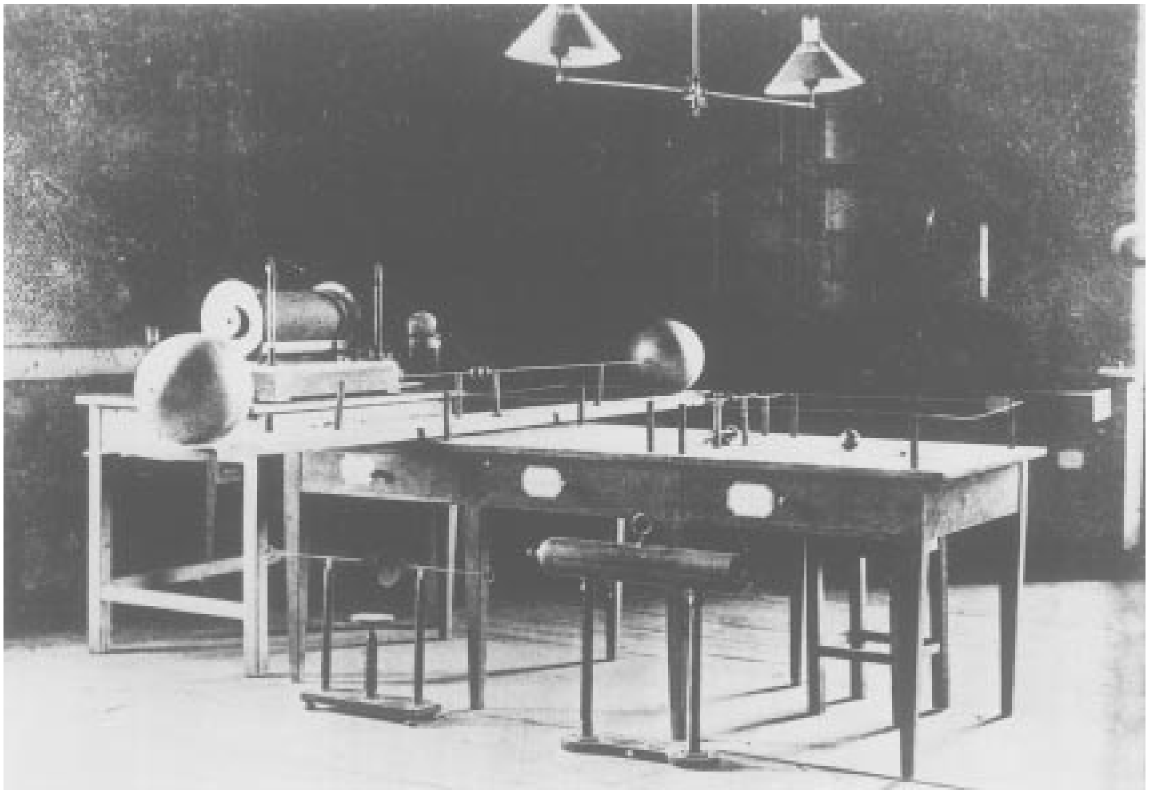

Fig. 3. Hertz's experimental setup at the University of Karlsruhe.

the age of 37 in 1894 and could not finish his thoughts on relativity. However, his experiments had opened the doors to radio and television (TV) broadcast stations, modern telecommunications systems, and all other microwave applications.

Recently, it could be shown that both the Maxwellians and their opponents were right [7], [8]. Taking the gradient of the Lorentz gauge $\mathrm{div}\boldsymbol{A} = -\varepsilon\mu\partial\varphi/\partial t$, we obtain

$$\mathrm{grad}\,\mathrm{div}\,\boldsymbol{A}_L = -\varepsilon\mu\,\mathrm{grad}\frac{\partial\varphi_L}{\partial t}. \tag{11}$$

Further, recognizing in the right-hand side of (11), divided by μ, Maxwell's displacement current $d\boldsymbol{D}/dt$, the magnetic vector potential wave equation can be readily written in the Coulomb gauge $(\mathrm{div}\ \boldsymbol{A} = 0)$ considering the displacement current as part of the forcing function on its right-hand side

$$\Delta\boldsymbol{A} - \mu\varepsilon\frac{\partial^2\boldsymbol{A}}{\partial t^2} = -\mu(\boldsymbol{J}_c + \boldsymbol{J}_d). \tag{12}$$

Including the displacement current $\boldsymbol{J}_d = \partial\boldsymbol{D}/\partial t$ in the forcing function yields the classical pair of potentials $\varphi_c, \boldsymbol{A}_c$ obtained in the Coulomb gauge. The potential φ_c is the solution of an "instantaneous" Laplace equation and $\boldsymbol{A}_c$ the solution of a magnetic vector potential *wave* equation, implying $\mathrm{div}\ \boldsymbol{A} = 0$. Formally, φ_c is indeed an instantaneously acting function. However, this instantaneous property is compensated by the lacking contributions of $\boldsymbol{A}_{\mathrm{irr}}$ in (9).

The early introduction of the artifice nowadays called a Lorentz gauge $\mathrm{div}\ \boldsymbol{A} = -\varepsilon\mu\partial\varphi/\partial t$ camouflaged for the opponents of Maxwell's theory the existence of the displacement current (according to Maxwell, the "German method"). Consequently, the concept of displacement current remained controversial over decades. Now that the semantics of the magnetic vector potential's irrotational component have been revealed [7], [8], physicists and engineers need no longer live with an only formally accepted concept but can readily understand what others debated for quite a while.

It is not surprising that Lorenz and others, in their time, considered their artifice very appropriate because they had gotten away without a displacement current, a concept that did not exist yet.

Having recognized in

$$\varepsilon\partial\boldsymbol{E}_{\mathrm{irr}}/\partial t = -\varepsilon\,\mathrm{grad}\frac{\partial\varphi}{\partial t} \tag{13}$$

the quasistatic displacement-current density $\boldsymbol{J}_{d_{\mathrm{irr}}}$ reveals all of a sudden the historic controversy's "simple" reason.

In this context, it should be mentioned that the Lorentz condition, that is, the "artifice," usually attributed to H. A. Lorentz (1853–1923), had been used many years sooner by Riemann and by the Danish physicist Lorenz [4].

III. Commercial Radio-Wave History

While Hertz and Maxwell were happy with the academic evidence of light's being an electromagnetic phenomenon, others valued more the electromagnetic waves' enormous potential for telecommunications. Among many subsequent telecommunications experiments with spark trans-

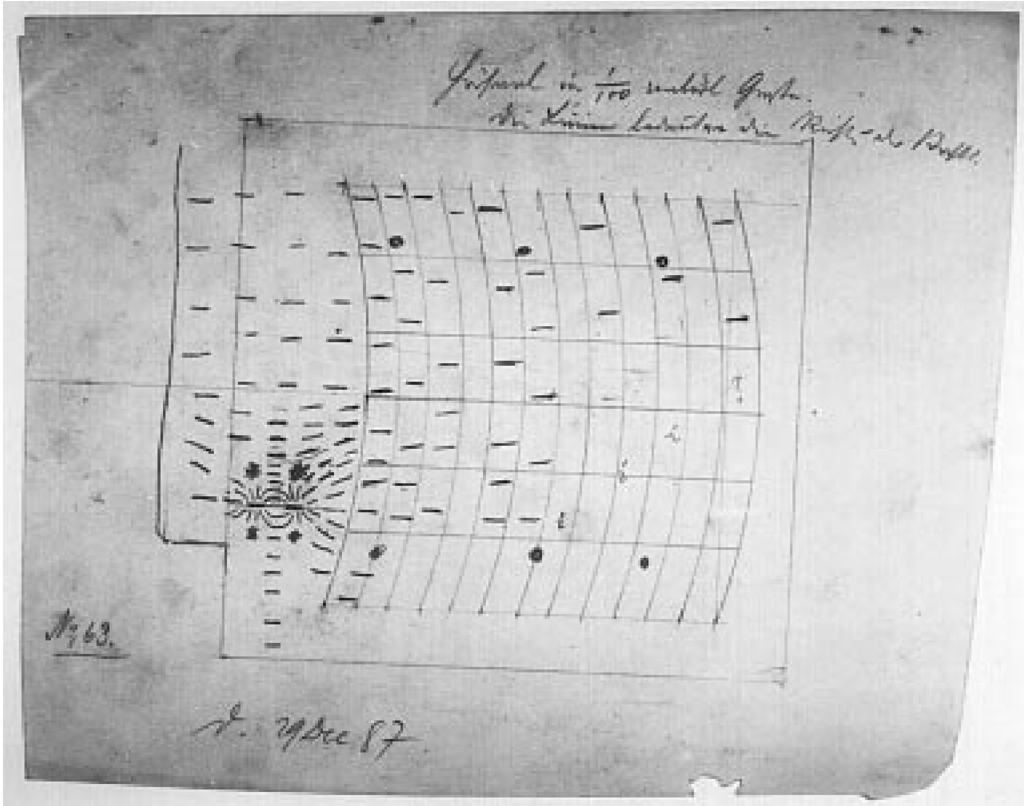

Fig. 4. Field sketch no. 63/1887, drawn by Hertz.

mitters made in various countries—for example, by *Hughes*, *Branly*, *Lodge*, and others—*Marconi* and *Popoff* excelled as genuine pioneers. In Germany, similar experiments were made by *Slaby* and *Braun*. In 1909, Marconi and Braun together received the Nobel Prize.

In 1897, Marconi and his partners founded in Great Britain the "Marconi Wireless Telegraph Co." In Germany, Slaby cooperated with AEG and Braun with Siemens. To eliminate the competition between both companies and in view of the huge market as well as the strategic importance of telecommunications, Siemens and AEG founded "Telefunken, Gesellschaft für Drahtlose Telegraphie mbH." In 1909, Marconi Wireless Telegraph Co. and Telefunken equally shared the world market almost exclusively (total number of telegraphy systems approximately 1600; approximately 700 installed by Marconi Wireless Telegraphy Co. and 700 by Telefunken.) Usually, the year 1903 is considered the milestone when radio waves went commercial.

The early commercial telegraphy transmitters were indeed high-voltage spark transmitters. A major improvement of their efficiency and radiating power was achieved by an impedance matching transformer between the ringing circuit and the antenna, invented and patented by Braun. Later, rotating machines exceeding 400 kW real power produced the long waves for transoceanic communications. Eventually, *continuous-wave oscillators* evolved based on the negative voltage/current characteristics of arcs or later on feedback-controlled vacuum-tube oscillators (until today). Vacuum-tube transmitters paved the way for radio and TV broadcast stations. The first German radio broadcast station began its operation in 1923, three years after the world's presumably first radio broadcast station in Pittsburgh, PA. Wavelengths became shorter every year and resulted, eventually, in TV broadcast stations, radar, microwave links, masers, satellite communications, powerful sea and air navigation systems, and, lately, mobile phones for everyone.

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Adolf J. Schwab (Fellow, IEEE) was born in 1937 in Mannheim, Germany. He received the M.S. and Ph.D. degrees in electrical engineering from the University of Karlsruhe, Germany, in 1961 and 1963, respectively.

In 1970–1971, he was a Postdoctoral Fellow with the Massachusetts Institute of Technology, Cambridge. In 1972, he became an Associate Professor at the University of Karlsruhe. He became a Professor at the University of Darmstadt, Germany, in 1976 and at the University of Dortmund in 1978. Since 1980, he has been a full Professor at the University of Karlsruhe. From 1989 to 1993, he was Director of the Corporate Research Center of ABB Germany, Heidelberg. Since then, he has been Director of the Institute of Electric Energy Systems and High-Voltage Technology at the University of Karlsruhe. He has written three books on *High-Voltage Measurement Techniques*, *Electromagnetic Compatibility*, and *Field Theory Concepts*, which have been published in several editions in German, Russian, and Chinese.

Dr. Schwab is a member of the Verband Deutscher Elektrotechniker, Conference Internationale des Grands Reseaux Electriques, IEEE Strategic Planning Committee, and IEEE Ethics Committee. He is the past Chairman of the IEEE Germany Section.

Peter Fischer (Member, IEEE) was born in Voelklingen, Germany, in 1969. He received the master's degree in electrical engineering from the University of Karlsruhe, Germany, in 1995.

In 1996, he joined the Institute of Electric Energy Systems and High-Voltage Technology, Karlsruhe. His current research interests include analytical and numerical calculation of electromagnetic fields in electromagnetic compatibility applications and high-performance computing.