Heinrich Hertz—Theorist and Experimenter

JOHN D. KRAUS, FELLOW, IEEE

(Invited Paper)

Abstract —**When Heinrich Hertz was appointed professor of physics at Karlsruhe in 1885 he was uniquely prepared for his historic experiments that opened the radio spectrum. He made the first antennas and transmitter–receiver radio system. He conducted a series of experiments which established in a brilliant way that radio waves are one with light except for their much greater length. His description of the radiation phenomenon remains the best ever written, revealing his tremendous depth of understanding of the subject. Hertz's training, studies, and experiments are recounted and measurements with a replica of his apparatus are described.**

I. Introduction

When Heinrich Hertz was born in Hamburg in 1857, Germany was a divided land of feudal kingdoms and towering castles, remnants of the Holy Roman Empire which had dominated Europe for nearly a millennium. During the next decade by bloodshed and iron, Otto von Bismarck forged a united German Empire riding on the crest of the Industrial Revolution and a gigantic chemical industry. Although a ruthless chancellor, Bismarck, like Frederick the Great and earlier kings of Prussia, was a patron of the arts and sciences and encyclopedic German universities flourished.

So when 21-year-old Heinrich Hertz entered the University of Berlin in the fall of 1878, Germany was a united empire and at the university he fell under the spell of a great seat of learning and in particular the influence of two famous pioneers of science, Gustav Kirchhoff and Hermann von Helmholtz.

Young Heinrich had already displayed unusual talents. As a boy, he had many interests, a trait that characterized his entire life. He made drawings, did all kinds of handicrafts, and became familiar with operating precision machine tools and lathes. He was fascinated by languages and eagerly studied Greek and Arabic. Other subjects into which he delved included psychology, political science, Kant's critique of pure reason, Darwinism, botany, zoology, mineralogy, and Plato's politeria.

Although his parents wanted him to become a construction engineer, his real love was for mathematics and physics. So after performing his military duties he pursued a scientific curriculum at the University of Munich and the Technical Institute there prior to entering the University of Berlin in 1878, where he studied under von Helmholtz.[1] A prize had been offered for an experimental demonstration of the effect of electromagnetic forces on dielectric polarization and von Helmholtz urged Hertz to enter the competition. Hertz considered whether the demonstration could be done with oscillations using Leyden jars or open induction coils. He concluded correctly that the effect would be too difficult to observe and did not pursue the problem. However, the seeds of interest in oscillations had been sown.

Hertz graduated from Berlin in 1880 with the rare citation of "Magna cum Laude". Three years later Hertz became Lecturer (Privatdozent) at the University of Kiel and in another two years, at the age of 28, he was appointed Professor of Physics at the Institute of Technology in Karlsruhe. He soon married Elizabeth Doll and during the next few years in this new setting began the historic train of events leading to his opening of the radio spectrum and his vindication of Maxwell's theory.

As we have seen, Hertz had a broad, diverse background and wide experience on which to draw. He was both a theorist and an experimenter. He possessed in every respect a "prepared mind." The stage was set and the play was ready to begin.

II. The First Radio Transmitter and Receiver

Hertz (Fig. 1) was at home with Maxwell's theory and the significance of the interrelation of electric and magnetic fields. Although Maxwell's theory had many skeptics, Hertz was not one and he realized, I feel certain, that vindication of Maxwell's theory would come only through experimental verification.

A common piece of laboratory apparatus at that time consisted of two coaxially mounted flat induction coils known as Knochenhauer spirals. A Leyden jar capacitor discharged through one coil (lower one in Fig. 2) induces a spark between the terminals of the upper coil.

In a series of steps Hertz replaced one Knochenhauer spiral by a straight wire having a spark gap at the center with a spark-producing induction coil connected across the gap. This straight wire Hertzian $\lambda/2$ dipole was a vital step because it was an *open* resonant system. Previous

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The author is the McDougal Professor Emeritus of Electrical Engineering and Astronomy, Ohio State University, Columbus, OH 43210.
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[1] Hertz dedicated his book *Electric Waves* "to his Excellency Hermann von Helmholtz with the deepest respect and gratitude."

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Fig. 1. Heinrich Rudolph Hertz (courtesy Burndy Library).

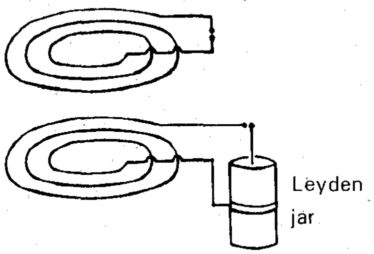

Fig. 2. Knochenhauer spirals with Leyden jar.

resonant systems were closed. In place of the other spiral, Hertz constructed a round or square single-turn loop with a small gap. A typical arrangement for the dipole and loop is shown in Fig. 3 as adapted from Hertz's drawing.

The next step was to demonstrate resonance. This Hertz did by adjusting the perimeter of the loop, with the results shown in Fig. 4. The resonant length (perimeter) is about 4.3 m, corresponding to a wavelength of about 8 m.

Hertz's apparatus of Fig. 3 included the first dipole antenna and with loop receiver was the first complete radio system. With it Hertz demonstrated tuning or resonance.

Hertz described the equipment of Fig. 3 and the above experiments done in 1886 and early 1887 in his paper "On Very Rapid Electric Oscillations" in volume 31 of *Wiedemann's Annalen*, published in 1887. Thus, this year or 1886 may be taken as the birth date of radio.

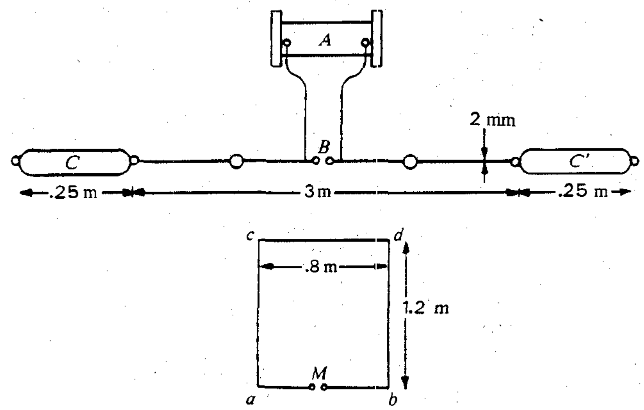

Fig. 3. Hertzian dipole and loop, the first radio transmitter–receiver system (after Hertz).

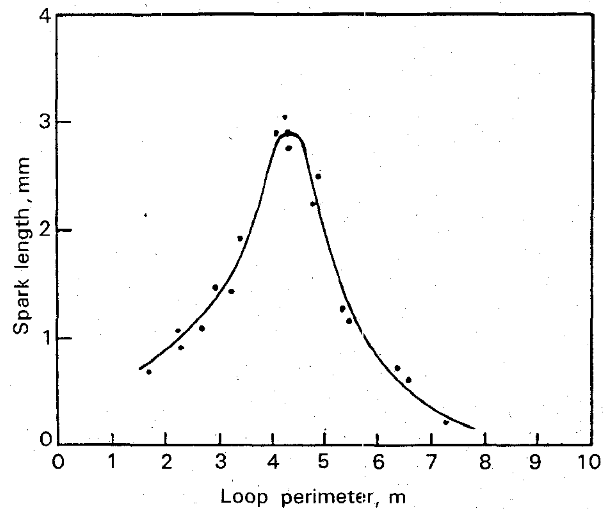

Fig. 4. Demonstration of resonance as a function of the perimeter of the loop receiving antenna (after Hertz).

III. Displacement Current

One of Maxwell's innovations was his introduction of displacement current ($\partial \boldsymbol{D}/\partial t$), that is, a current resulting from a changing electric displacement ($\boldsymbol{D} = \epsilon \boldsymbol{E}$) in empty space or in a dielectric. To demonstrate the existence of displacement current Hertz devised a clever scheme with which he showed that a paraffin block has a current-carrying effect for radio waves similar to that of a metal sheet. This was experimental proof that Maxwell was correct.

IV. Standing Waves on Wires

Next Hertz succeeded in setting up standing waves on a long straight wire and measured the spacing between successive standing wave minima. This gave him the wavelength (equal to twice the spacing).

V. Skin Effect

In another demonstration Hertz surrounded a long wire by a parallel-wire metal cage and found that when the cage was closed at its ends around the wire, current no longer flowed along the wire but rather outside the cage. He thus demonstrated the "skin effect" or the restricted depth of penetration of RF into a conductor.

He further states "the disturbance in the wire itself is not, as has hitherto been assumed, the cause of the phenomena in its neighbourhood; but that, on the contrary, *the disturbances in the neighbourhood of the wire are the cause of the phenomena inside it*."

VI. Standing Waves in Air

Next came observations of standing waves in air. Hertz placed a large flat zinc plate vertically at a distance from his $\lambda/2$ dipole transmitter. Using a resonant loop, he was able to detect maxima at 3 m spacing for a wavelength of 6 m. Here was proof of Maxwell's prediction that electromagnetic oscillations propagate as a wave through space. The direct wave and the one reflected back from the zinc plate interfered to produce a standing wave like the interference fringes of a Newton color glass or an oil slick on water except that the radio waves are a million times longer.

VII. Beaming, Reflection, and Refraction

To concentrate or beam his 6 m waves Hertz realized that he would require a parabolic reflector of enormous proportions. Accordingly, he built a new system for 1/10 the wavelength (or 60 cm) with a spark-gap-fed $\lambda/2$ dipole 30 cm long at the focus of a cylindrical parabolic reflector of zinc sheet 2 m (or 3.3λ) tall by 1.2 m (or 2λ) across. This was for transmitting. For receiving, he placed a center-fed full wavelength dipole at the focus of an identical parabola bringing a two-wire transmission line from the center of the dipole through insulating bushings to the back side of the parabola, where he installed an adjustable spark gap.

With these parabolas Hertz was able to observe the beaming of radio waves and could work to a distance of 16 m, transmitting his waves through a closed wooden door from one room to another in his laboratory. He then put his parabolas side by side and bounced his waves from one to the other via a large flat zinc sheet. He was able to demonstrate that the angle of reflection from the flat sheet equaled the angle of incidence.

To demonstrate refraction Hertz built a massive prism of asphalt 1.5 m high with 1.2 m sides meeting at a 30° angle and placed it on a turntable between his parabolas. Measuring the angle of incidence and the deviation by the prism, Hertz was able to determine an index of refraction which was close to the optical value.

VIII. Polarization

With parabolas vertical and facing each other, response was a maximum but turning one parabola horizontal reduced the response to zero, demonstrating linear polarization. With both parabolas again vertical, he placed a large grid of vertical parallel wires between the parabolas, cutting off transmission. But if the grid wires were set at an angle or turned horizontal a response was obtained. Further, with transmitting parabola vertical and receiving parabola horizontal for zero effect, inserting the grid at an angle produced a response. Hertz's grid wires behaved like the atomic lattice of a calcite crystal to light.

Hertz described the above experiments with his parabolas in the paper "On Electric Radiation," published in the *Sitzungbericht der Berliner Akadamie der Wissenschaft*, December 13, 1888. The paper also appeared the next year in volume 36 of *Wiedemann's Annalen*.

IX. The Hertz Vector

In Hertz's extensive theoretical calculations he introduced a vector quantity

$$\Pi = \frac{1}{4\pi\epsilon j\omega}\iiint \frac{\boldsymbol{J}}{r}\,dv$$

involving the current density $\boldsymbol{J}$ $(=J_0 e^{j(\omega t-(r/c))})$ from which both the electric and magnetic fields $\boldsymbol{E}$ and $\boldsymbol{H}$ could be determined at any distance r. The quantity Π is called the *Hertz vector* and has appeared frequently in the literature on electromagnetic radiation.

X. The Fields from a Dipole

From his calculations of the fields radiated from a short dipole antenna, Hertz published the first diagrams showing the development and outward movement of the electric fields radiating from an antenna. These diagrams, reproduced in Fig. 5, show the status of the electric field at four instants of time separated by intervals of 1/4 of a period. Hertz described in detail how the field near the dipole has both radial and transverse components but at a large distance the field is entirely transverse with the field, decreasing inversely with the distance and with a sine-shaped pattern. He also noted that close to the dipole the phase velocity of the wave is superluminal ($v > c$).

This discussion by Hertz of the behavior of the electric and magnetic fields as they leave the dipole and travel out into space is the most thorough and lucid account I have ever read. Hertz even points out the locations near the dipole (shown by circular arrows in Fig. 5) where circular cross-field exists. It is a tribute to Hertz that as the first person to describe the phenomenon of radiation from an antenna, his presentation remains the best, revealing his tremendous depth of understanding and mastery of the subject. Hertz published these diagrams in his article "The Forces of Electric Oscillations, Treated According to Maxwell's Theory" in volume 36 of *Wiedemann's Annalen*, 1889.

XI. Hertz's Apparatus

Hertz's demonstrations of the similarity of his waves to light are impressive, especially when you view the size and extent of his apparatus seen in Fig. 6. This photograph shows Hertz's original equipment. At the top (1) is the wire surrounded by a cage for demonstrating the skin effect. Below it (2) is the 30° asphalt prism on a turntable and behind it is the large flat zinc reflector. At the right (3), beside the custodian, is one of Hertz's parabolic reflectors with vertical $\lambda/2$ dipole at the focus for operation at 60 cm

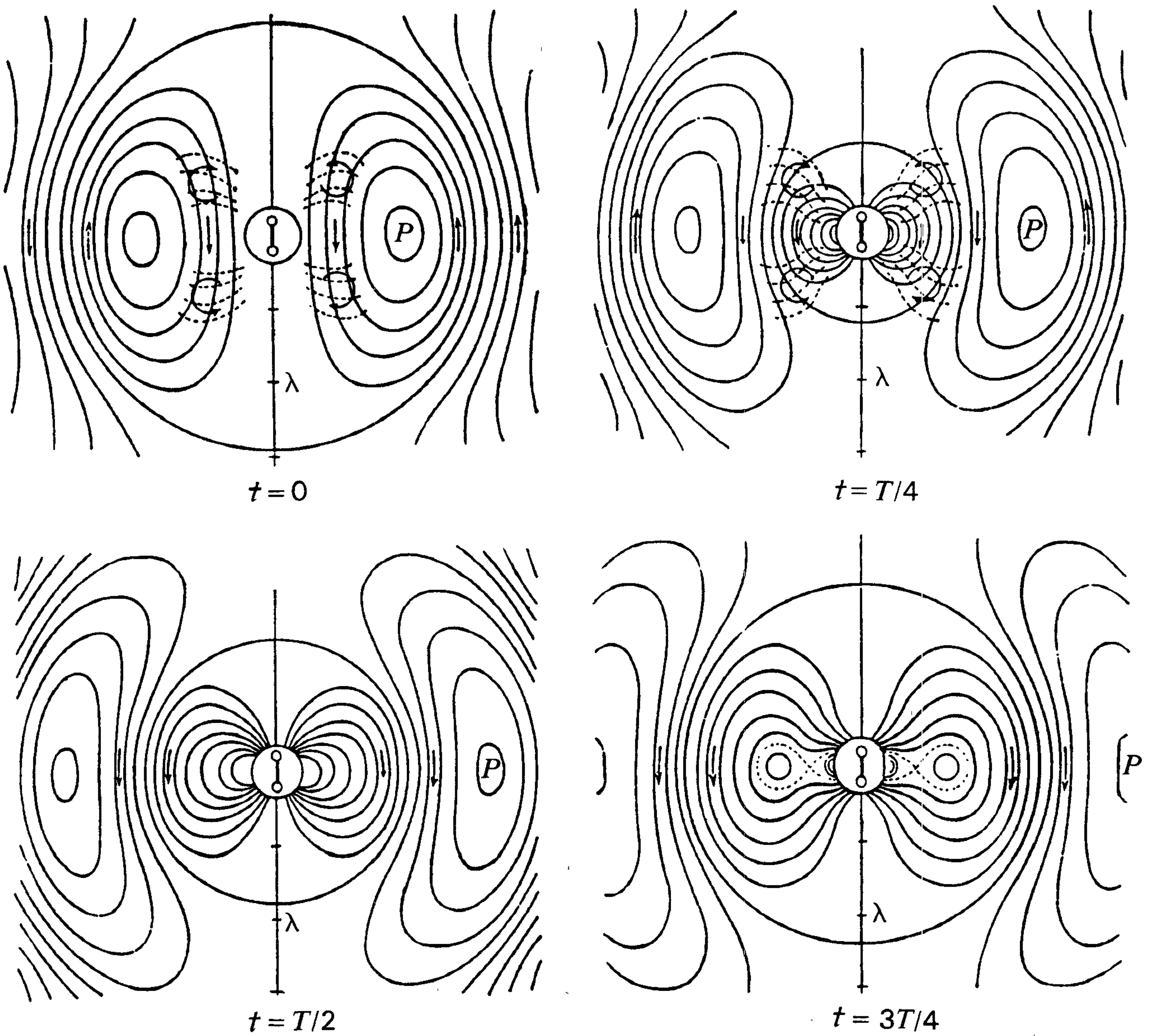

Fig. 5. Electric fields of a radiating dipole antenna at four instants of time (0, 1/4, 1/2, and 3/4 of a period) (after Hertz).

wavelength. His other parabola is at the left (4). At the far left is the large grid of parallel wires Hertz used in his polarization experiments. On the floor in the foreground (5) is his sphere-loaded $\lambda/2$ dipole with spark gap at the center. In addition, there are round, octagonal, and square frames for his resonant loop receivers, a large Ruhmkorff and a smaller Keiser and Schmidt induction coils, Knochenhauer spirals (6), and a variety of other equipment.

XII. Modern Replicas

Every modern laboratory course in radio should include apparatus for Hertz's experiments. I have developed an extensive set of Hertzian and other experiments as part of a lecture–demonstration using 3 cm waves generated by a Gunn oscillator. At 3 cm wavelength the spread fingers of one hand can be substituted very effectively for a grid of parallel wires to demonstrate polarization effects. I conclude my lecture–demonstration with a reenactment of Heinrich Hertz making observations with a replica of his resonant square loop on the waves radiated from a replica of his $\lambda/2$ dipole with bright blue sparks jumping the gap between the brass balls at its center.

I built these replicas of Hertz's apparatus with spark gaps operating at meter wavelengths to understand and appreciate more fully the details of his system. My best working model is an end-loaded $\lambda/2$ dipole 2 m long with a spark gap at the center as transmitting antenna and a $\lambda/2$ perimeter loop as receiving antenna, as in Fig. 7, patterned after Hertz's system of Fig. 3. To generate sparks, I connect two Ford Model-T spark coils back-to-back. This provides a balanced feed. A single Ford spark coil is unsatisfactory because one end of the secondary coil is connected internally to the primary, making the output unbalanced. With a dc input power of about 30 W to the spark coils, enough RF is generated to observe sparks at the gap in the loop at a distance of about 3 m broadside to

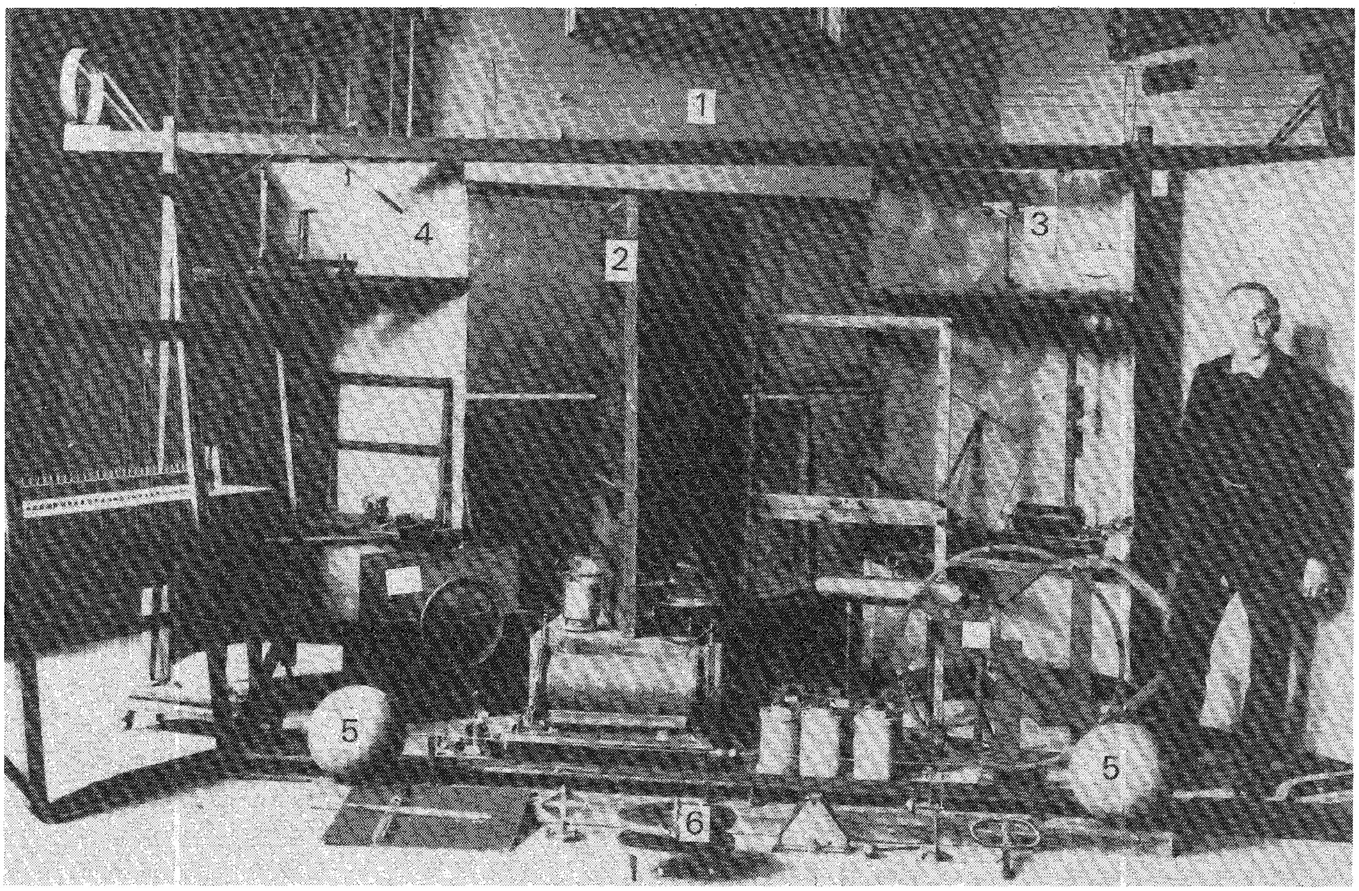

Fig. 6. Heinrich Hertz's original apparatus which he used in his epoch-making experiments at the Institute of Technology at Karlsruhe. Photograph taken in 1913 at the Bavarian Academy of Science in Munich, where the equipment had been transferred. (Photograph courtesy of the Museum of Science and Technology, Chicago.)

the dipole or into the zone where radiation is dominant.[2] Judging from the size of Hertz's spark coils, it is apparent that he operated at much higher power. A spark is a very inefficient RF generator so my equipment probably generated less than a watt average RF power and Hertz's not much more. However, peak powers are higher and are enough to demonstrate the principles. Hertz calculated that one of his transmitters had a peak input power of 16 kW.

Moving or translating my loop parallel to the dipole, the maximum sparking occurs in the center position (as in Fig. 7), with sparks diminishing as the loop is moved nearer either end of the dipole. This indicates a current maximum at the center of the dipole.

With no spark, the gap is open and its resistance is that of the spark coil secondaries (about 5000 Ω). When the interrupter breaks the primary circuit a high secondary voltage is induced across the gap. When it exceeds the dielectric strength of the air, a spark jumps the gap, the voltage drops, and so does the gap resistance. The rapid change in current with time (dI/dt) generates damped radio-frequency oscillations over a broad spectrum with

[2] For radiation to be dominant, measurements need to be made at a distance greater than $\lambda/2\pi$ for a short dipole and somewhat farther for a $\lambda/2$ dipole.

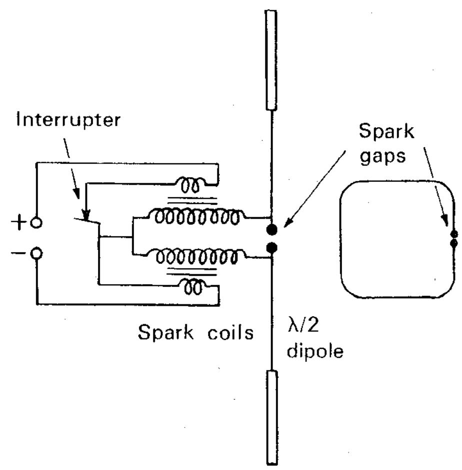

Fig. 7. Replica of Hertz dipole and loop system built and operated by the author.

the dipole resonating and radiating some of this RF energy.

As Hertz makes clear, it is important to distinguish the real RF phenomenon from the electrostatic effects associated with the high voltages of a spark system. Thus, if a $\lambda/2$ dipole like the transmitting one is substituted for the loop as a receiver, it is possible to get sparks at the gap in the receiving dipole when it is parallel and close to the "transmitting" dipole, even without any sparks at the gap connected to the spark coil.

To facilitate adjustment of conductors and equipment, Hertz used rubber bands and sealing wax. I also found rubber bands (heavy ones) useful. But I had an advantage over Hertz: I had Scotch electric tape.

Recalling Hertz's 16 m link between his two parabolas raises the question: Did Hertz ever consider using his Hertzian waves for communication over a long distance? No doubt he did, but, as he found and as I can confirm from my experience, a simple spark gap receiver is very insensitive and severely limits the range. Hertz once tried a frog's leg, which had been suggested as possibly being more sensitive but it wasn't. It was not until a decade later, after the much more sensitive coherer of Edouard Branly and Oliver Lodge had been developed, that longer ranges became possible.

It is a tragedy that Hertz did not live to see his great gifts to the world utilized, his untimely death in 1894 cutting short a productive and promising career.

XIII. Conclusion

To make my measurements in the clear, I set up my Hertz replicas on a large flat area near my home where I conducted my observations at night to better observe the tiny sparks at the gap in the loop. For me, it was a highly emotional experience to recreate as best I could what Hertz had done a century before. I realized then, as never before, the magnificence of the epoch-making steps Hertz had taken, which opened the whole radio spectrum to mankind's utilization. From such simple, yet effective, apparatus has come all of radio communication, AM, FM, TV, links that span the solar system, and radio waves from quasars at the edge of the universe. Could Hertz or anyone of his time have envisioned all of this? And can we now imagine where new applications of Hertzian waves may yet take us in the next 100 years? Thank you, Heinrich Rudolph Hertz, for your magnificent, monumental work!

Acknowledgment

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John D. Kraus (A'32–M'43–SM'43–F'54–LF'76) was born in Ann Arbor, MI, in 1910 and received the Ph.D. degree in physics from the University of Michigan in 1933. He then did research in nuclear physics with Michigan's newly completed 100-ton cyclotron until World War II, when he worked on the degaussing of ships for the U.S. Navy and on radar countermeasures at Harvard University. After the war he came to the Ohio State University, where he is now Director of the Radio Observatory and McDougal Professor (Emeritus) of Electrical Engineering and Astronomy.

He is the inventor of the helical antenna, the workhorse of space communication; the corner reflector, used by the millions for television reception; and many other types of antennas. He designed and built the giant Ohio radio telescope known as "Big Ear." He is the holder of many patents and has published hundreds of scientific and technical articles. He is also the author of the widely used textbooks *Antennas* (McGraw-Hill, 1950; 2nd ed., 1988), *Electromagnetics* (McGraw-Hill, 1953; 2nd ed.; 1973, 3rd ed., 1984), and *Radio Astronomy* (McGraw-Hill, 1966; 2nd ed., Cygnus Quasar, 1986). In addition, Dr. Kraus has written two popular books, *Big Ear* (1976) and *Our Cosmic Universe* (1980).

Dr. Kraus received the U.S. Navy Meritorious Civilian Service Award in 1946. He was elected to the National Academy of Engineering in 1972. He received the Sullivant Medal, Ohio State University's top award, in 1970; the Outstanding Achievement Award of the University of Michigan in 1981; the Edison Medal of the IEEE in 1985; and the Distinguished Achievement Award of the Antennas and Propagation Society of the IEEE in the same year. Currently, Dr. Kraus is serving as antenna consultant to government and industry.