HEINRICH HERTZ AT WORK IN KARLSRUHE

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The confirmation of Maxwell's electrodynamical theory by Heinrich Hertz in the years 1887/8 was not a straight-on work. The generation and handling of oscillations of very high frequency had to be developed and misleading results to be interpreted. After preliminary experiments a powerful oscillator and transmitter was invented, exited by a spark. The radiated field was detected by secondary sparks in a wire-loop, which was tuned to resonance, also a new invention at that time. The finite velocity of the propagation of electromagnetic action was definitively proved by the detection of standing waves. Further experiments showed the similar nature of electromagnetic waves and light very clearly. Later Hertz verified the theoretically predicted skin-effect.

This is a well known fact: Heinrich Hertz confirmed Maxwell's "Dynamical Theory of the Electromagnetic Field" experimentally in Karlsruhe during the two years 1887/8. How he did this, why he started this work at this time and the problems he had to overcome, that shall be the content of the following paper.
Hertz had been confronted with the existance of more than one competing electromagnetic theories already, when he was a student at the university of Berlin in the year 1879. His mentor, Professor Helmhotz, perhaps the most important physicist in Germany at that time, who was very interested in that problem, had suggested to him to undertake experiments in his institute, which would confirm one or another result of Maxwell's theory and with that win a price, which was offered by the Berlin Academy of Science. After some preliminary calculations Hertz came to the conclusion, that the highest frequencies, which were attainable at that time, would not be sufficient to produce a reasonable effect from the displacement currents. Therefore he refused the suggestion.

In the spring 1886 he got a chair as professor of physics at the "Technische Hochschule" (institute of technology) in Karlsruhe, the capital of the duchy Badenia in Germany. Here he had his own institute with experimental possibilities. In the next year, in the spring of 1887, when preparing experiments for physical lectures, he made observations, which led him to the conclusion, that now he should be able to decide between the competing electrodynamical theories and to fulfil the conditions for the price of the Academy.
The exitation of oscillations up to ca. 1 MHz in resonant circuits had been investigated by Feddersen long before. Hertz experimented with a pair of flat coils, destinated to demonstrate the magnetic induction. If a condensor was discharged through one of the coils, one would get secondary sparks at the output of the other one. Hertz observed such secondary sparks, when the primary circuit included no condensor, if the energy source, a high-tension transformer, was connected to the coil via a primary spark-gap. Hertz connected this observation with the fact, that in a circuit, containing two spark-gaps in series, one of them shunted with a wire loop, both spark-gaps would show sparks, when a condenser was discharged through this circuit. He concluded, that in both cases contributions of frequencies much higher than those of Feddersen should be involved.
Up now, besides his professional duties and social obligations, Hertz concentrated his work on one aim, to verify or perhaps to disprove the Maxwell theory. But this was a long way. He went on very systematically. At first he replaced the primary flat coil with its not well defined stray capacity by an so called open circuit, a straight wire with metallic spheres at both ends, interrupted in the middle by a spark-gap and a high-tension transformer connected directly to the spark-gap. Already for his first preliminary experiments he used this form of the primary circuit, which proved later

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to be his most important invention, the dipole-oscillator and -antenna. He approximately could calculate the resonance frequency of this circuit, the capacity of the spheres from a well known static formula, the inductivity of the connecting wire by formulas given by the competing theories and differing from each other, but only in a comparatively small amount.
Hertz replaced the secondary coil by a wire, 20 inch long and bent to a nearly closed rectangular loop with an adjustable spark-gap to observe secondary sparks. At that time no other detector for high-frequency oscillation was known than this spark-gap. This circuit was connected to the primary circuit by a single wire. If this wire was connected to the point opposite to the spark-gab, so that the two ways from the connecting point to the two electrodes of the spark gap were equal, no secondary sparks were observed, otherwise the spark-gap fired. Hertz explained this by the finite velocity of the electrical exitation along the wire, going from the connecting point in both directions and cancelling at the spark-gap, if the travelling times are equal and causing a potential-difference for a short time, if not.
This explanation holds only, if the front of the exitation is very steep or if oscillations of very high frequency occur.

Hertz tended to the second explanation. If quick enough, the primary spark should exite his open resonator to damped oscillation as well, as it had done withe the coil-and-condenser-circuit of Feddersen. He got another argument for this, when he replaced the galvanic coupling between his primary and secondary circuit by an inductive coupling. A wire parallel to one side of the secondary circuit and 3 cm apart, was connected with one end to one side of the primary circuit, with the other end to a so called conductor, a metal sphere or cylinder, acting as a condenser to the surroundings and causing a reasonable current through this wire. Though this arrangement gave secondary sparks as well as the galvanic coupling, the induced current had no physiological effect, as Hertz called it. I think, the touch of the primary circuit caused a very unpleasant feeling and Hertz had been very surprised, when this did not happen with the inductively coupled circuit. A single shot of current surely would have caused the so called physiological effect.
It would be tiresome to desribe all experiments in detail. Hertz did a lot of variations of his arrangements and anyway he got experience to handle high-frequency circuits.

The next important progress and at the same time the evidence of the oscillatory nature of the observed facts was the observation of resonance effects. The intensity or, better measurable, the maximal length of the secondary sparks dependet on the size of the secondary circuit. To investigate this effect and detect resonance phenomena, the primary circuit was made of a wire, 2.6 m (ca. 8.5 feet) long and two spheres, 30 cm (ca. 1 foot) in diameter, which could be shifted along the wire. Tuning of the primary circuit was much easier, than of the secondary. The secondary circuit was coupled inductively in a distance of more than 30cm. With this arrangement real resonance-curves were received. Now the tools seemed to be ready to begin the work on the proof of Maxwell's theory. But before Hertz did that, he observed an unexpected effect: The sensitivity of the secondary spark-gap depended on the mutual position of the primary and the secondary spark-gap. This of course had an influence on the reliability of his measurements and he had to investigate this effect before going further. By screening the path between the two sparks with different materials he found, that this was caused by the ultraviolet light, which was emitted by the primary spark. Though this was a very interesting fact, he abandoned the research an this object as soon, as he had omitted possible errors in his further planned measurements caused by this effect. The proof of Maxwell's theory was the more important thing, the nature of the photo-effect could be investigated by others.

His detector, the above described secondary circuit was capable not only to give information about the existence of alternating electric as well as magnetic fields, but also about their direction, especially after he replaced the rectangular loop by a circular one. If the sparks remained uneffected, when the loop was turned around its axis, they must be caused by a magnetic field, if there occured two minima, then by an electric field. By turning the loop around an axis in its plane, it is possible to measure the direction if the field. But when Hertz tried to measure the whole field around his primary oscillator, he found some points, where he got sparks in any direction of the loop. He concluded that at this points the polarization must be circular, but he found no explanation of this fact. This, he thought, was not in agreement with Maxwell's theory, but it was too early, to make conclusions to this. Later, after he had succeeded with other experiments he developed an algorithmus to calculate the field of the so called Hertzian dipole exactly and than he found the circular electric and magnetic field just at the place, where he had measured it before.

The next experiment was an direct attempt to the confirmation of one result of Maxwell's theory, the induction-effect of displacement-currents in insulators. To confirm this result had been one of the conditions to win the Academy-price. Hertz replaced the oscillator with the spheres by a flat one, which carried metal plates instead. It is a result of electrostatic theory, that an electric field, caused by charges on conductors, will be altered only in intensity, not in its form, when a piece of insulating material is brought into the field, so that the surface of this material is parallel to the electric field or in direct contact with the charged conductors. Now if a block of insulating material is brought near the flat oscillator, so that one surface of it lies in the symmetry plane of the oscillator, another surface in direct contact with the metal plates and the other surfaces far enough away not to make a reasonable effect, than said conditions are fulfilled. First this insulator is removed and a secondary loop so adjusted, that the sparkgap is in a position, in which the magnetic field is of no influence and the effect of the electric field is cancelled by symmetry, so no sparks are observed. After that the insulating material is put in the described position. If the displacemant-currents do not exist or have no inductive effect, than the symmetry condition in the secondary circuit should not be altered and no sparks should occur. Otherwise, if the results of Maxwell's theory are right, the secondary circuit should show sparks and it has to be turned somewhat around its axis to restore the symmetry condition and remove the sparks.
This experiment had a positive result with different insulating materials. Nevertheless it was not yet a convincing proof of Maxwell's theory, only a disproof of the existing competing theories. The most important assumption of Maxwell was not the existence of displacement-currents in insulators, but in the vakuum and the inductive effect of them. Really convincing would be the proof of a finite velocitiy of propagation of electromagnetic action not only in transmission lines, which had been made long before, but in the free space, especially in the vakuum. Hertz decided to do just this in his next experiment.

Hertz already had observed, that his primary oscillator had an effect on the secondary one at an unexpected long distance, more, than should be explainable by ordinary induction, but his measurements were quantitatively uncertain and not sufficient for such conclusions. To get information about the velocity of waves in free space he had the idea to use interferences between free waves and waves, transmitted by a straight wire of sufficient length. To measure the velocity of the wire-waves he used a somewhat shorter wire and observed standing waves at the far end of this wire. For the interference experiment the wire was 200 feet long, passed through a window and ended in an earth-connection, so that no disturbance of the interference by a reflected wave was to be expected. This wire was exited by the same oscillator which was expected to radiate a free wave. By proper orientation of the secondary detector-circuit the influence of the wire-wave as well as that of the free wave could be observed separately and, with other orientations of the detector-circuit, both waves simultaneously and so the interference. The result of this experiment was the following: The free wave travelled with the velocity of light in accordance with Maxwells theory, but not the wire-wave, it was retarded by the factor 28/45. This was not in accordance with Maxwell's theory and Hertz found no explanation for it. He repeated this measurement a number of times, but got no other result. The question, by what this fact was caused, has not been solved in detail till now. But at that time Hertz and other physicists did not realize, that a single wire is no transmission line and the influence of the return line, maybe the earth, cannot be neglected. Insofar the experiments of Hertz with wire-waves were not fully defined.

Hertz himself was not very lucky with this result and thought of the possibility, that Maxwell's theory should be not quite complete. Therefore he decided to undertake another more convincing experiment, to observe standing waves in free space, which would give in connection with the calculated frequency of the oscillator a good result for the velocity of this waves. For that he needed a big room and took the biggest available one, the lecture room. This room has survived the second world-war, it is 45 feet long, 2o feet high and was at the time of Hertz free of obstacles 30 feet wide. The gas-tubes and -lamps he ordered to remove temporarely, the seats of the students, which could not be removed, were covered with wood-planks and a plate of zinc 5 to 10 feet large, mounted at one side, to give a better reflection. The experiment was quite successful, the wavelength was ca 8m, what means, the frequency had been ca 37 MHz.

That coincided sufficiently with the calculated value and Hertz was satisfied by that. But his intention went further. He tried, to focuse the electromagnetic radiation by a parbolic mirror, in analogy to the focusing of visible light. Of course the attempt to do that with waves longer than the dimensions of the mirror failed and Hertz had to overthink the problem to exite oscillations of much higher frequency as befor. He did not write much about the attempts to do this, he only describes the solution. In the following, I will cite his own words in the translation by D.E.Jones, published 1893:

> Imagine a cylindrical brass body, 3cm in diameter and 26 cm long, interrupted midway along its length by a spark-gap whose poles on either side are formed by spheres of 2 cm radius. The length of the conductor is approximately equal to the half wavelength of the corresponding oscillation in straight wires; from this we are at once able to estimate approximately the period of oscillation.

This small oscillator easily could be mounted in the focal line of a cylindrical parabolic reflector, 6 1/2 feet high and with a focal length of 5 inches. A similar reflector served as focuser for the receiver. There arose another problem, the loop-detector could not be placed properly in th focal line. Hertz developed a non resonant dipol antenna, long compared to the wavelength, with a transmission line to a spark-gap outside of the reflector. With this set of transmitter and receiver he demonstrated all features of optical radiation, refraction, reflection, polarisation and to some extent diffraction. This was a very convincing demonstration of the similar natur of electromagnetic radiation and light and a splendid confirmation of Maxwell's theory, but it could not serve as the last proof of the electromagnetic nature of light. That was done much later by Purcell and coworker 1953 (3).

Further experiments, which Hertz did in Karlsruhe were of not as much importance, as those described before. He confirmed another result of Maxwell's theory, the skin-effect. But for this purpose he invented the coaxial shielded line, of cour course without any knowledge of the later impotance of this tool. But this is another indication, that Hertz was not only a splendid researcher but also a capable inventor and he created the foundations not only of transmission by electromagnetic waves, but also of the handling of very high frequency oscillations.

References:

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