Revisiting the 1888 Hertz experiment

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We revisit the original experiment performed by Hertz in 1888 and use a simple setup to produce electromagnetic waves with a frequency in the range of 3 MHz. By doing a Fourier analysis of the signal captured by a resonant antenna, we can study the behavior of the RLC series circuit, frequency splitting of coupled resonances, and the characteristics of the near-field emitted by the loop antenna.
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Heinrich Hertz is best known for his series of experiments conducted from 1886 onward with which he demonstrated that the predictions of Maxwell were correct.[1,2] In particular, he showed that it is possible to generate electromagnetic (EM) waves that propagate in free space with a well defined frequency and wavelength, it is possible to observe interference between these waves, and most importantly, that these waves transport energy. In the same group of experiments Hertz also observed for the first time many other effects, most notably the photoelectric effect. Notwithstanding the importance and impact of these experiments it is uncommon to find these experiments reproduced in some form or another. The purpose of this paper is to describe an experimental setup that is a modification of the original setup and yields insight and direct measurements of many aspects related to EM emission. Among these are a clear demonstration of power transmission, a precise characterization of loop antenna emission, the observation of frequency splitting due to resonator coupling, and the near-field decay of the electric and magnetic fields created by a loop antenna.

The setup we used is a simple (RLC) circuit (see Fig. 1). A capacitance C of 1 nF (15 kV maximum voltage[3]) is connected to a 1 m diameter loop antenna A obtained by bending a simple piece of copper tubing (1 in. diameter). The inductance of the antenna L was measured with this setup and found to be roughly 5 μH; using different diameter tubing does not significantly change this value. The resistance of the circuit is provided directly by the circuit, for example, the antenna has $R=1.2\ \Omega$. The circuit is powered by a 6 kV transformer T, which may be found from a neon-light dealer at low cost. An important part of the circuit is the spark-switch S inserted in one of the arms between the capacitor and the antenna. The switch was constructed by taking two rounded bolts with a housing that lets us regulate the distance between the rounded extremities. The 6 kV voltage supply oscillates at 50 Hz. As the voltage on the capacitor increases, the voltage also increases between the two extremities of the bolts. The breakdown threshold in air is $\sim$3 kV/mm, so that if the air gap is correctly adjusted, a spark will close the RLC circuit once a voltage difference of $\sim$6 kV is reached. The circuit will then start to oscillate at a frequency of $(1/2\pi)\sqrt{LC}\sim 2$ MHz.[4]At each oscillation a large percentage of the power (of the order of 30%) will be lost due to emission from the loop antenna, that is, by the generation of propagating EM waves. These waves may then be recaptured using a second loop antenna (RA) identical to the emitting antenna A, with a series capacitor with the same value as C. We also used a 15 kV transformer, although in this case problems may arise with the capacitor. The maximum voltage rating for the transformer is typically 15 kV or less, so that it is necessary to use at least two in series (and another two in parallel so as to maintain the same effective capacitance). We also had to insert the capacitors into a plastic bottle (a large soft drink) filled with oil to avoid dielectric breakdown in the air gap between the wires protruding from the capacitors.

It is possible to demonstrate energy transport by attaching a small light bulb to the receiving antenna RA. This experiment is best performed using a 15 kV transformer. By placing the receiving antenna at a distance of the order of 1 m or slightly more, it is possible to light the bulb. Although the light tends to flicker, we found much better stability by using a spark switch divided into two, that is, we used three bolts in series so that sparks were generated across the two airgaps.

For a quantitative analysis of the EM emission we used the 6 kV transformer and attached the receiving antenna to a digital oscilloscope (for example, Tektronics TDS 1002) with which we were able to download the data to a personal computer [do not keep laptops or (LCD) screens between or near the antennas]. For the RLC circuit the charge on the capacitor is given by[4]

$$Q = Q_0 e^{-Rt/2L}\cos(2\pi\nu t + \phi), \quad (1)$$

with $\nu=\sqrt{1/LC-(R/2L)^2}$. In Fig. 2 the dots show an example of a $V(t)$ trace obtained by measuring the voltage difference on the capacitor with the receiving antenna placed 1 m from the emitting antenna. A short build-up time is followed by the expected exponential decrease, but the oscillation does not follow a perfect cosine. By taking the Fourier transform of the $V(t)$ trace we observed two distinct frequency peaks at $\nu_1=1.95$ MHz and $\nu_2=2.88$ MHz, as shown in Fig. 3. Hence, the shape of $V(t)$ is due to a beating between two different frequencies. In Fig. 2 we also see that

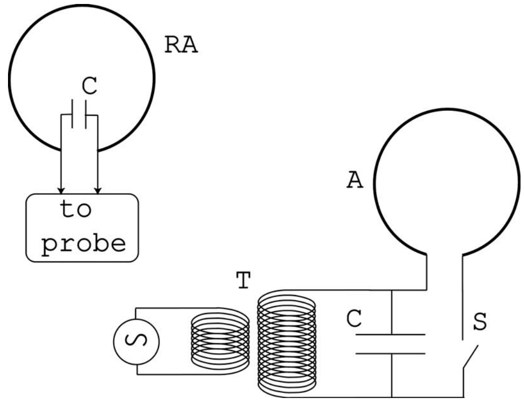

Fig. 1. Layout of the experiment: A is the emitting antenna (1 m diameter copper-tube loop), C represents a 1 nF capacitor, S is the spark switch, T =220 V/50 Hz to 6 kV/50 Hz transformer and RA represents the receiving antenna.

this beating dies out after $t \sim 4$ μs, leaving a sinusoidal oscillation at $\nu = \nu_2$. The reason for this behavior is that during the first oscillations of the circuit, a very large EM field is emitted. This field is captured by the receiving antenna which in turn reemits, thus modifying the behavior of the RLC circuit. In other words the inductances of the two (receiving and transmitting) loop antennas are coupled. As the oscillations die away, the emitted field becomes much smaller, returning the circuit to the ideal RLC state. This behavior is analogous to that observed with Tesla coils. In this case a similar beating between two slightly different oscillation frequencies is observed and is due to the periodical coupling of energy between the primary and secondary coils. The apparatus described here is similar in many aspects to the Tesla coil with the emitting loop antenna playing the role of the Tesla primary and the receiving antenna that of the Tesla secondary coil.

More quantitatively, we observe a splitting of the natural resonance frequency ν_0 of the antennas into an up-shifted and a down-shifted frequency, a very general phenomena of coupled systems ranging from the hydrogen molecule to coupled optical waveguide modes. The split frequencies are related to the natural resonance frequency by a dimensionless coupling coefficient q:[5]

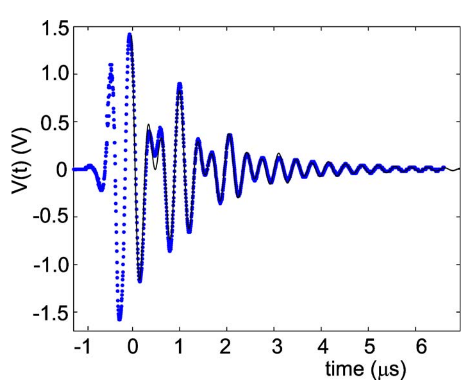

Fig. 2. Measured potential V versus time (dots) and best fit obtained using Eq. (4) (solid line).

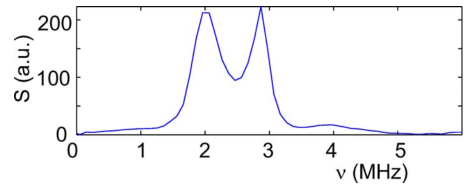

Fig. 3. Fourier transform of the $V(t)$ trace shown in Fig. 2.

$$\nu_1 = \frac{\nu_0}{\sqrt{1+q}} \tag{2a}$$

$$\nu_2 = \frac{\nu_0}{\sqrt{1-q}}. \tag{2b}$$

For $\nu_2 = 1.95$ MHz and $\nu_2 = 2.88$ MHz as found from Fig. 3 we obtain $\nu_0 = 2.28$ MHz and $q = 0.37$. The value of ν_0 can be checked by exciting the antenna and capacitor (LC circuit) with a cosine signal at various frequencies and searching for the resonance condition.

To fit the $V(t)$ data we use the following phenomenological relation:

$$V(t) = V_0 e^{-\alpha t}[(\cos(2\pi\nu_2 t) + \cos(2\pi\nu_1 t))(1 - e^{-k/t^2}) + \cos(2\pi\nu_2 t)e^{-k/t^2}]. \tag{3}$$

The first term describes the beating of the two oscillations at ν_1 and ν_2. This beating term is weighed by an exponential function that depends on t and is adjusted (by the parameter k) so that at $t \sim 4$ μs the second term describing a simple oscillation at ν_2 dominates. The best fit is shown as a solid line in Fig. 2 and gives $R = 6.1$ Ω and $L = 4.9$ μH. We note that Eq. (3) describes an exponentially decaying beating between two cosine waves. Therefore it is not able to reproduce

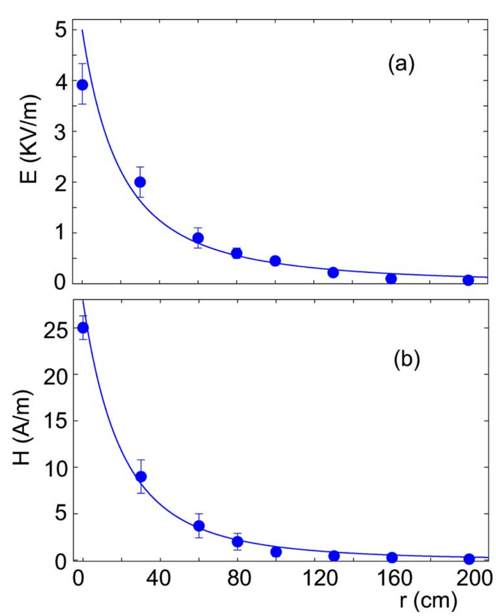

Fig. 4. (a) Electric field intensity versus distance measured along the loop antenna axis. The solid line shows the $1/r^2$ fit. (b) Magnetic field intensity versus distance; the solid line shows the $1/r^3$ fit. The dots represent the experimental data.

the experimental behavior for negative times (in Fig. 2), that is, for the initial buildup of energy in the antenna circuit. The value for L agrees with results from a sweep test performed with a signal generator, and R also accounts for the energy loss mediated by the antenna A.

It is not possible to easily reproduce all of Hertz' results with this setup. In particular, it is not feasible to measure the wavelength. However, this apparatus is ideal for characterizing the near field decay rate (for example, along the axis of the antenna A) of the electromagnetic field emitted from a loop antenna. It is expected that the near field ($r \leq \lambda$) should decay much faster than the far field. In particular, the magnetic field should decay as $1/r^3$ and the electric field as $1/r^2$.[6] By removing the receiving antenna and measuring the E and B fields along the antenna axis using an EM field meter (Wandell & Goltermann EMR-20), we obtain the results shown in Figs. 4(a) for the E field and in Fig. 4(b) for the B field. We see that the data reproduce the $1/r^2$ and $1/r^3$ dependencies quite well. We note that it has been predicted[6] that the E field goes to zero for $r=0$, whereas we find that although there is a deviation from the $1/r^2$ curve, E is still far from zero. This result might be a consequence of an averaging effect due to the relatively large size of the meter sensor or more likely is due to spurious reflections and contributions coming from the surrounding environment.

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SPACE AND TIME TO SPACETIME

The incorporation of space and time into a modern scientific context goes back to Newton in the 1600s, but serious thought regarding their microscopic makeup required the twentieth-century discoveries of general relativity and quantum mechanics. Thus, on historical time scales, we've really only just begun to analyze spacetime, so the lack of a definitive proposal for its ''atoms''—spacetime's most elementary constituents—is not a black mark on the subject. Far from it. That we've gotten as far as we have—that we've revealed numerous features of space and time vastly beyond common experience—attests to progress unfathomable a century ago. The search for the most fundamental of nature's ingredients, whether of matter or of spacetime, is a formidable challenge that will likely occupy us for some time to come.

Brian Greene, *The Fabric of the Cosmos: Space, Time, and the Texture of Reality* (Knopf, 2004), p. 486.