

Electromagnetic radiation: megahertz to gigahertz

A tribute to Heinrich Rudolf Hertz and John Turton Randall

M.J. Lazarus, B.Sc., D.Phil., C.Eng., M.I.E.E., Sen.Mem.I.E.E.E.

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Abstract: The original background to the discovery of electromagnetic waves is described. It is shown that many of the extremely high-frequency techniques, which have been used in modern times, can be traced back to Heinrich Hertz himself. The influence which Hertz's work had on the invention of the cavity magnetron by Randall and Boot is described in somewhat more detail than has hitherto been published.

'The idea of physical reality still remained purely mechanistic. One still sought to interpret all happening as the motion of inert bodies; indeed one could not imagine any other way of conceiving things. Then came the great revolution which will be linked with the names of Faraday, Maxwell, Hertz for all time'.

Albert Einstein

List of symbols

H	= magnetic field strength
D	= electric displacement
E	= electric field strength
B	= magnetic flux density (magnetic induction)
J	= electric current density
A	= magnetic vector potential
c	= velocity of electromagnetic waves
μ_r	= relative permeability
μ_0	= permeability of a vacuum
ϵ_r	= relative permittivity
ϵ_0	= permittivity of a vacuum
t	= time
π	= Hertz vector
i, j, k	= unit vectors for x, y, z directions
r	= radial distance from origin
P	= dipole moment
P_0	= peak amplitude of oscillating dipole moment
I	= electric current
Q	= electric charge
dl	= element of length
ω	= angular frequency ($2\pi f$)
r, θ, ϕ	= spherical polar co-ordinates
\wedge	= vector product

1 Introduction

In 1885 a young professor named Heinrich Hertz was appointed to the Technische Hochschule in Karlsruhe. In the Spring of 1886 Hertz began a series of experiments which culminated in the discovery of radio waves, and



[Courtesy of Professor Wolfgang Paul]

Fig. 1. Professor Heinrich Hertz circa 1889

which, apart from leading to revolutionary effects on human communication, established once and for all the reality of Faraday's suggestion that electric forces can persist in space independently of their original causes. Maxwell [1] had created the mathematical framework for Faraday's ideas and predicted that these electric forces would propagate in a way which identified them with light waves. However, few scientists of the time grasped the significance and, indeed, the clarified forms of the 'Maxwell equations' which we all use today represent yet more achievements on the part of Oliver Heaviside and Heinrich Hertz. Hertz's discovery was in no way sudden. it was, in Sir J.J. Thomson's words: 'one of the most marvellous triumphs of experimental skill, of ingenuity, of caution in drawing conclusions in the whole history of physics'.

Hertz's early and sad death so soon after his great discoveries meant that the applications were left to others; notably Marconi (first, in Italy and, later, in England) and Popov, in Russia. Much less well known, however, is the influence Hertz's work had more than half a century later

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The author is with the Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom

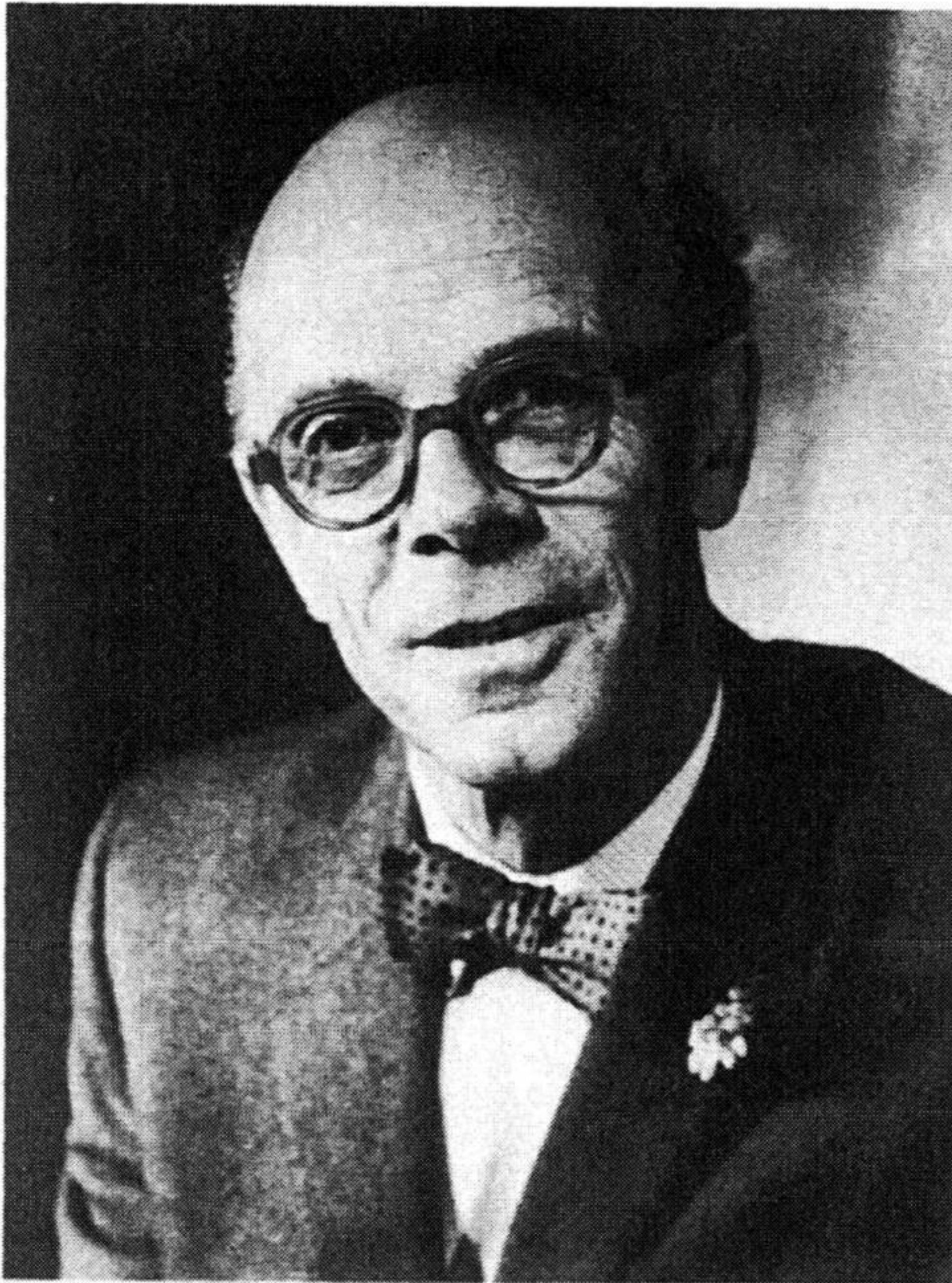
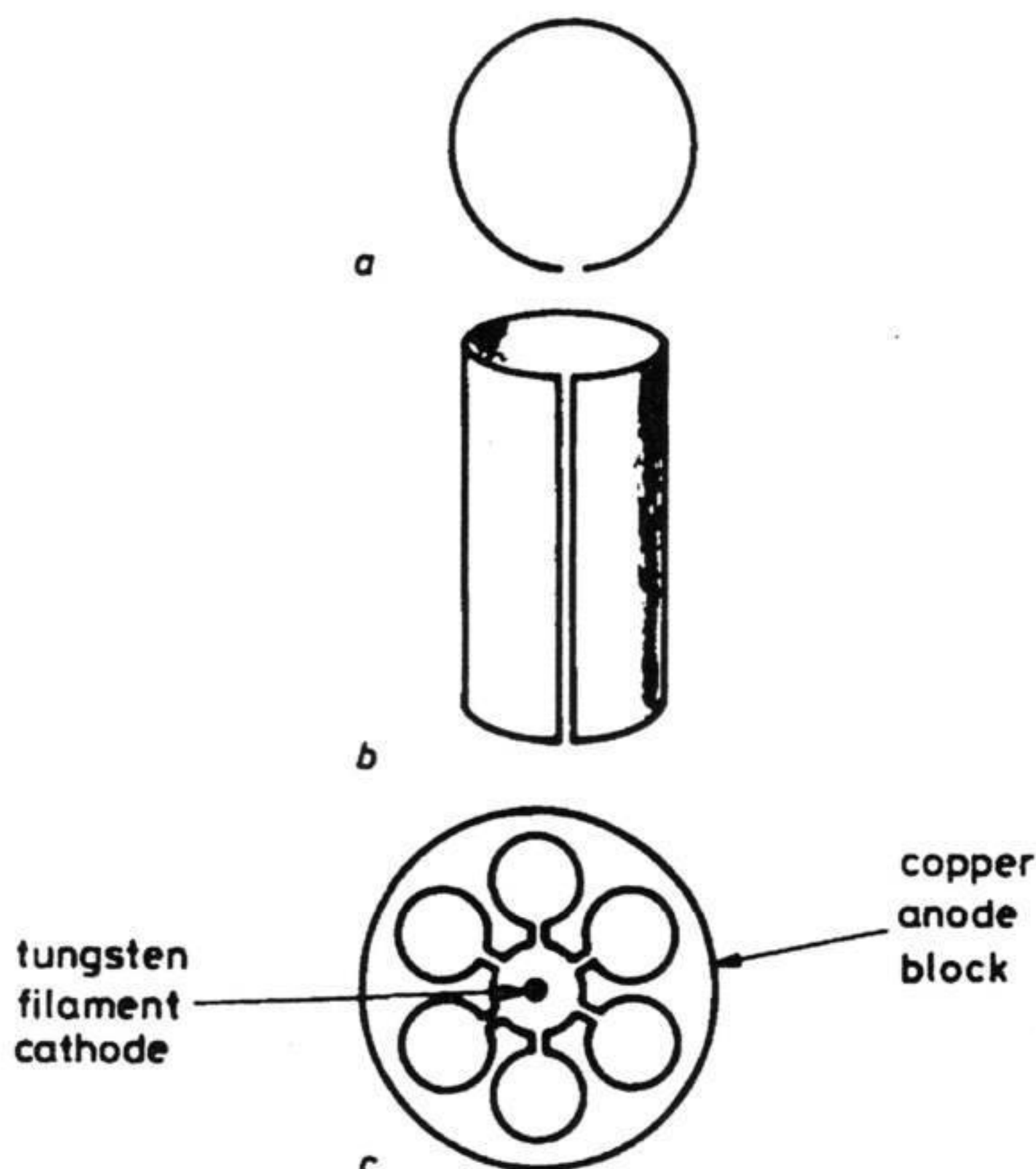


Fig. 2 Professor Sir John Randall F.R.S. circa 1963
Portrait by Godfrey Argent for the National Portrait Gallery

on the development of the radar cavity magnetron. Indeed it was Hertz's invention of small circular resonators which inspired Randall to conceive cylindrical extensions of these resonators. In 1939 Randall and Boot constructed a cluster of six such resonators in the anode block of their magnetron. Early in 1940 the Randall-Boot resonator mag-



[Prepared with the kind assistance of Prof. Sir John Randall, F.R.S.]

Fig. 3 Evolution from the loop resonator of Heinrich Hertz to the cavity magnetron of Henry Boot and John Randall

a In 1887, Hertz constructed a ring of wire with a spark gap to detect electromagnetic waves
b In 1939, Randall read of Hertz's technique and extended the ring to a cylinder
c Together with Boot, Randall tested six such extended 'Hertzian resonators' cut from a copper block. The swirling electrons in the combined electric and magnetic fields excited these cavities which acted as coupled resonators.

netron or 'cavity magnetron' was already generating hundreds of watts CW at wavelength less than 10 cm: the success of the Hertz resonators was immediate!

2 Biography

Heinrich Hertz was born in Hamburg in 1857, the son of a scholarly linguist father who was a lawyer and eventually a Senator of the City. Other relatives had interests in commerce and natural sciences, and with these influences Hertz acquired keen intellectual and practical abilities. He studied engineering and physics and won considerable distinction for his contributions to the theory and practice in both subjects. It is the purpose of this review to focus attention on the approaching centenary of his greatest work: the discovery of electromagnetic waves and the verification of Maxwell's theory.

Hertz studied under Helmholtz and Kirchhoff in Berlin where later he became Helmholtz's assistant. He progressed to lecturer at the University of Kiel and then professor at the Technische Hochschule at Karlsruhe in 1885, where he conducted the famous experiments. In 1889 he was appointed to the prestigious professorship at Bonn, but, tragically, he died in 1894. The exact cause of his death remains a mystery, although blood poisoning and bone malignancy were reported.

3 Background to Hertz's work

The impact that Heinrich Hertz's work had on the contemporary scientific community is vividly recorded by the great teacher-professor, Arnold Sommerfeld, in his famous book 'Electrodynamics'. In the 1880s, when Sommerfeld was a student, the picture of electrodynamics was 'awkward, incoherent, and by no means self contained'. Scrutiny of the literature leading up to that period shows that many scientists regarded Maxwell's theory as just one of many rival theories — and incapable of being tested experimentally. Students were presented with a confused mass of observed facts and a mixture of theories; some of them doubtful. Sommerfeld described his experience: 'It was as though scales fell from my eyes when I read Hertz's work . . . Here Maxwell's equations purified by Heaviside and Hertz were made the starting point of the theory'. It is interesting to note that Sommerfeld refers to 'The simplified forms of the Maxwell equations, later rediscovered by Heaviside and Hertz'. Indeed, notwithstanding the bewilderment of so many contemporaries, the co-ordinate forms of $\text{curl } \mathbf{E} = -(\partial \mathbf{B} / \partial t)$ and $\text{curl } \mathbf{H} = \mathbf{J} + (\partial \mathbf{D} / \partial t)$ were inconspicuously published by Maxwell as early as 1861 in the *Philosophical Magazine*, Vol. XXI [2].

In the introduction to his book 'Electric waves', Hertz describes how he was inspired by Helmholtz's prize problem to attempt to detect the interaction between the polarisation of insulators and the electromagnetic field. In our modern notation we understand such phenomena from the Maxwell equations $\text{curl } \mathbf{H} = (\partial \mathbf{D} / \partial t)$ and $\text{curl } \mathbf{E} = -(\partial \mathbf{B} / \partial t)$. It is all too easy for us to take these for granted. For example, we can recognise instantly that the second equation represents the EMF induced per unit area of an infinitesimal loop according to Faraday's Law — but for this we are indebted to the clarification of Maxwell's meaning performed by Hertz and Heaviside. For most scientists of the day, Maxwell's theory was at best an 'unfamiliar mass of equations and concepts' [4], and the superiority of Maxwell's theory over its rivals was still to be demonstrated by Hertz. It is perhaps ironic that Riemann's introduction of retarded potentials, in 1867,

was an attempt to rival Maxwell's fields, as it was Hertz's combination of two concepts which enabled him to compute the radiation fields from his oscillating dipole! However, before Hertz's experiments, Maxwell's theory was based on little more than the intuition of Faraday and the uncertain significance of the discovery made by Weber and Kohlrausch in 1856 that the ratio of electrostatic to electromagnetic charge equalled the velocity of light. It was for precisely these reasons that Helmholtz and the Berlin Academy of Sciences set up the prize problem directed to the testing of Maxwell's theory, at a time when Hertz and Heaviside were two of the very few supporters of Maxwell's wave theory.

4 Hertz's identification of electromagnetic waves

A complete review of the researches of Heinrich Hertz would require several hundred pages, even to begin to do justice to them. Quite apart from his researches in electromagnetics, Hertz investigated the mechanical safety of railway trains, hardness of materials, and discovered the photoelectric effect. Several excellent accounts of selected experimental topics have already been published [5-8]. Rather less has been written about his mathematical work, despite the fact that his analyses are still the bases for modern calculations of radiation fields from antenna elements. The formulation of his theoretical equations not only founded the theory and practice of radio but also guided the thoughts of the great pioneers of modern physics [9, 10].

We shall review a selection of the highlights of Hertz's work. Of his vast number of experiments, perhaps the most famous and important were those which identified radio waves with light waves and verified Maxwell's electromagnetic wave theory. They were, in fact, research works which we would now call 'microwave optics' experiments (with wavelengths ≈ 60 cm).

Prior to these, however, Hertz first needed to develop techniques for generation and detection and to identify that there was indeed a radiation field travelling with finite velocity. He succeeded in all of these aims and even established the electromagnetic wave field patterns in standing waves caused by reflection. Typical of his semipictorial diagram is Fig. 4 which shows one of his dipole transmitters AA' with a spark gap energised from the induction coil

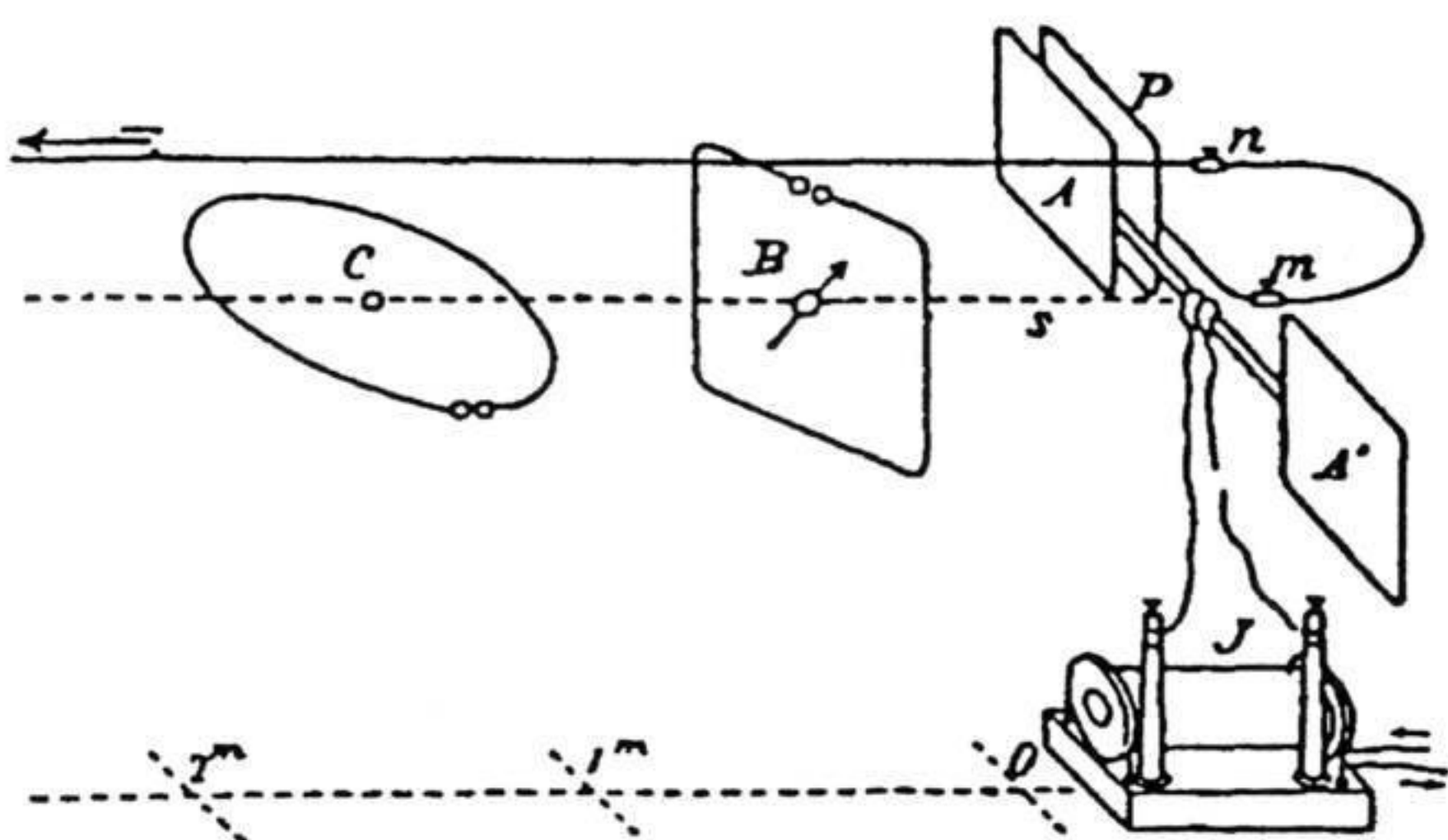
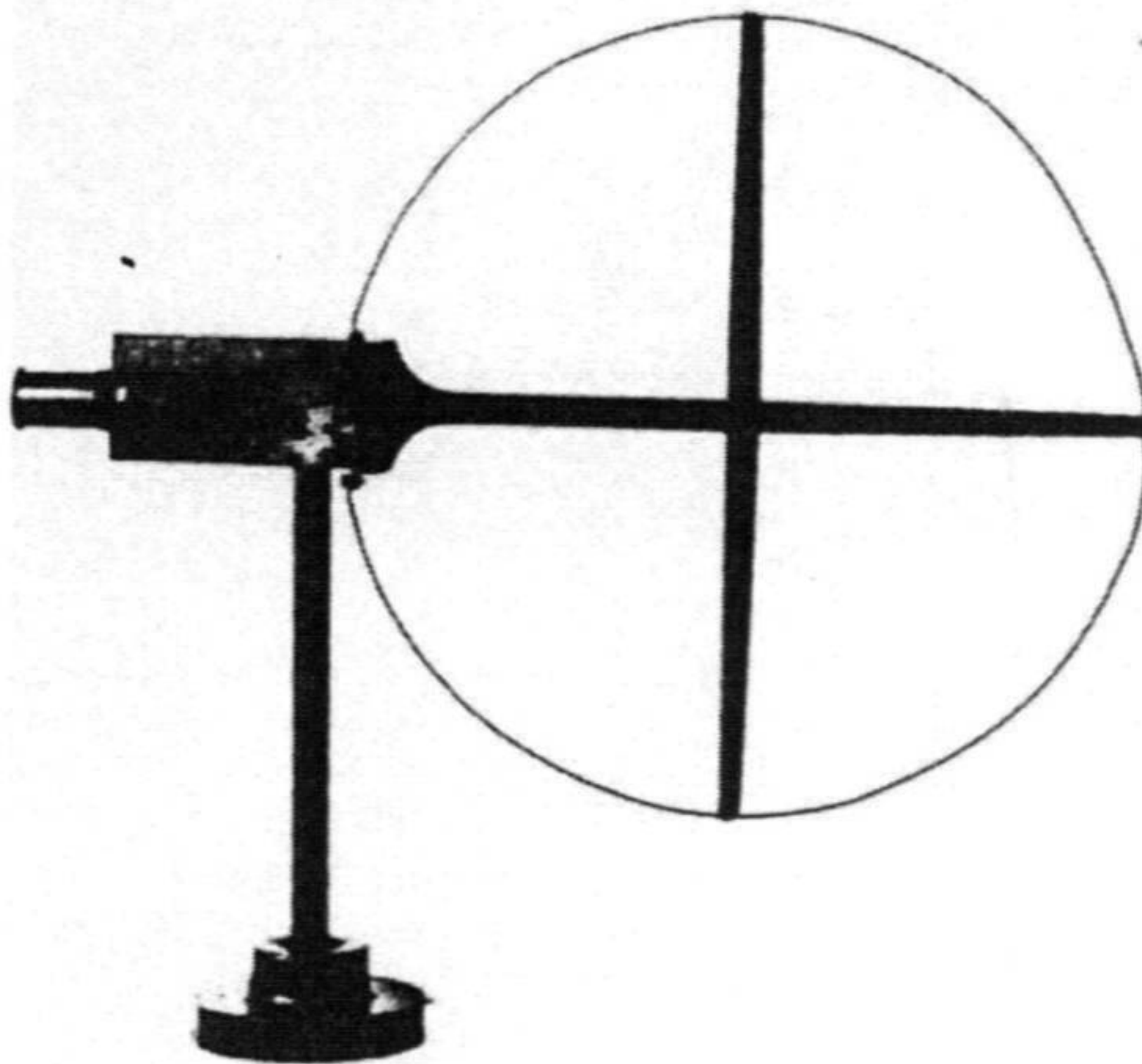


Fig. 4 Hertz's spark transmitter with two of his loop detectors

J. He frequently used resonant loops with spark gaps as detectors, sometimes a rectangular loop B , and sometimes a circular loop C . The mathematical basis for the resonance of this circular loop resonator was the driving inspiration for the development of the resonators of the cavity magnetron more than half a century later, as we shall see. Fig. 5 shows a photograph of one of Hertz's circular loop resonators, now preserved at Karlsruhe.

There were many other finer details which Hertz investigated. For example the 'skin effect' had been predicted by



[Photograph: courtesy of the Chancellor of Karlsruhe University, formerly the Technische Hochschule, where Hertz discovered radio waves]

Fig. 5 Hertz constructed this circular resonator for wavelength = $7.95 \times$ diameter to detect electromagnetic waves

Randall developed this remarkable resonator, in collaboration with Boot, for the cavity magnetron

Oliver Heaviside in 1885. This was verified by Hertz using thinner and thinner metal envelopes. Eventually he surrounded his detecting circuit with 'glass tubes which had been chemically silvered' and he detected the radiation only when the film of silver was 'certainly thinner than $1/1000$ mm'.

Hertz also discovered that, when light from the transmitter spark illuminated the receiver electrodes, the latter sustained a much stronger spark. By using an optical spectrometer he demonstrated that the ultraviolet portion of the light was responsible. This was, of course, the photoelectric effect; eventually to be explained by Einstein's photoelectric equation.

Hertz described ingenious techniques for determining the direction of electric and magnetic field vectors by rotating and orienting his loop detector and observing the sparks caused by the detected fields. His delightful style of combining profound investigation with homely techniques is exemplified in his description of the plotting of the radiation field around his antenna by drawing lines of force on a large wooden floor with chalk. These patterns, he explained mathematically with his famous analysis of the 'Hertzian dipole' radiator, in which he showed how the electromagnetic wave fields could be derived from the 'Hertz vector'.

5 The Hertz vector

In his paper 'The forces of electric oscillations treated according to Maxwell's theory'* Hertz introduced the vector π , now known as the 'Hertz vector'. This is in fact related to the vector potential A through $A = (1/c^2) \cdot (\partial\pi/\partial t)$. More recent authors still use different constants of proportionality. Sommerfeld (Reference 4, p. 149) writes $A =$

* *Ann. Phys.*, 1889, 36, (1). This is available in English as Chapter IX of 'Electric Waves', Reference 3

$\mu_0(\partial\pi/\partial t)$, whereas Stratton (Reference 11, p. 28) uses $A = (1/c^2) \cdot (\partial\pi/\partial t)$.

It is interesting to compare the Hertzian dipole field expressions in terms of A and in terms of π (except that we shall rewrite Hertz's original formulation in modern SI units).

First, we note the general formulation:

$$\mathbf{H} = \frac{1}{\mu_r \mu_0} \text{curl } \mathbf{A} = \frac{1}{\mu_r \mu_0} \frac{1}{c^2} \text{curl} \left(\frac{\partial \pi}{\partial t} \right) \quad (1)$$

and, from $\text{curl } \mathbf{H} = \epsilon_r \epsilon_0 \dot{\mathbf{E}}$, we have

$$\begin{aligned} \mathbf{E} &= \frac{1}{\epsilon_r \epsilon_0} \int \text{curl } \mathbf{H} dt \\ &= c^2 \int \text{curl curl } \mathbf{A} dt \\ &= \text{curl curl } \pi \end{aligned} \quad (2)$$

For a vector potential or Hertz vector parallel to the z -axis, the above equations immediately yield the original form of Hertz (Reference 3, p. 140). For example,

$$\begin{aligned} \mathbf{E} &= i \frac{\partial}{\partial x} \frac{\partial \pi}{\partial z} + j \frac{\partial}{\partial y} \frac{\partial \pi}{\partial z} + k \frac{\partial^2 \pi}{\partial z^2} - \nabla^2 \pi k \\ &= i \frac{\partial}{\partial x} \frac{\partial \pi}{\partial z} + j \frac{\partial}{\partial y} \frac{\partial \pi}{\partial z} - \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \pi k \end{aligned} \quad (3)$$

The modern approach of expressing the 'curl curl' operator in spherical polar co-ordinates would have had little or no audience at that time, as witnessed by the almost lone struggle which Hertz's friend and correspondent, Oliver Heaviside, was having in his attempt to introduce vector analysis against the opposition of authority!

5.1 The forces around a rectilinear oscillation

As a student of Helmholtz and Kirchhoff, Hertz would certainly have been well aware of the retarded potential for the solution to the inhomogeneous wave equation (Reference 11, Chapter VIII, p. 424), since the scalar form had already arisen in the study of acoustical wave transmission and propagation. As mentioned in Section 3, Riemann introduced retarded potentials to rival Maxwell's fields in 1867! It was therefore natural for Hertz to test the concept of an oscillating dipole moment with (again converted to modern notation) a 'Hertz vector' potential:

$$\pi = \frac{1}{4\pi\epsilon_0} P_0 \frac{\sin \omega \left(t - \frac{r}{c} \right)}{r} k \quad (\text{for dipole along the } z\text{-axis}) \quad (4)$$

For modern antenna synthesis it may seem more appropriate to convert the dipole moment to a current element through: $Idl = (dQ/dt) dl = dP/dt$. However, let us consider Hertz's original concept of the oscillating dipole moment — for this yields a quite beautiful set of physical pictures of the mechanism of radiation. These are shown in Fig. 6, and are slightly simplified forms of those which Hertz presented in his original paper.

In Fig. 6a the dipole is uncharged, the current and dP/dt are at maximum, while the rate of change of current dI/dt and d^2P/dt^2 are instantaneously zero. The terms of the fields which carry away net power as radiation are in fact proportional to dI/dt or d^2P/dt^2 . (The field lines drawn in Fig. 6a are those already propagating outward from a previous half cycle of radiation.)

In Fig. 6b the dipole is being charged up and the field lines are appearing. This diagram represents the situation

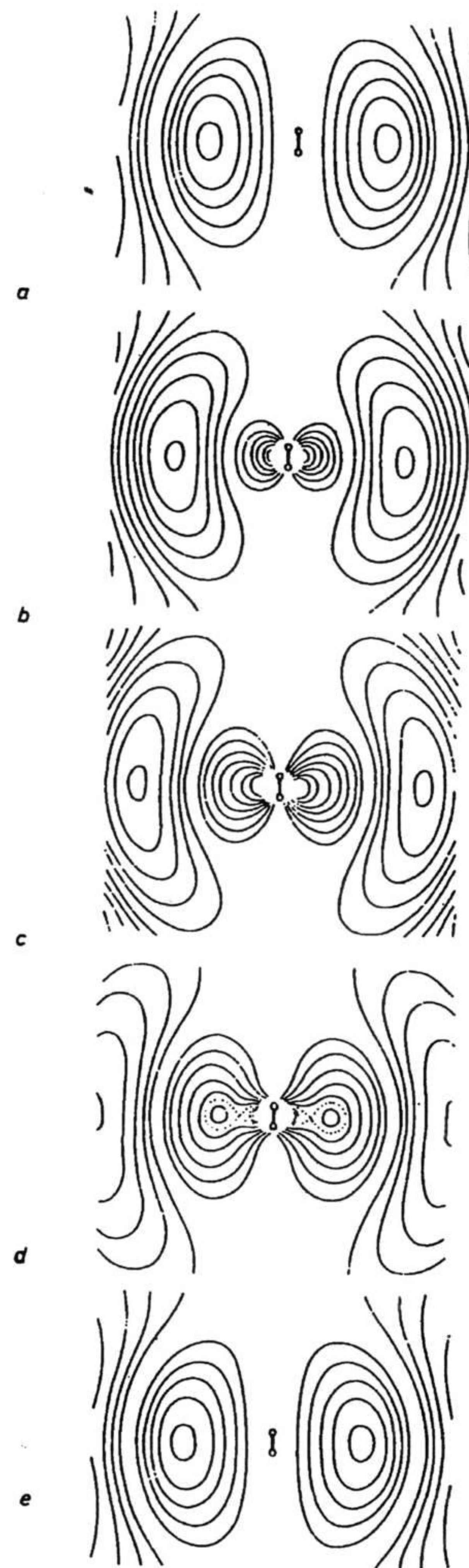


Fig. 6 The electric wave field patterns which Hertz derived for his oscillating dipole

The diagram shows successive eighth periods for one half cycle of oscillation

after one-eighth time period of oscillation, taking time zero to be that for Fig. 6a.

Fig. 6c shows the field pattern after one-quarter period. The dipole has now been charged to its maximum with the maximum number of lines of force. The dipole is about to contract.

Fig. 6d represents the situation during contraction of the dipole strength at time three-eighths period. The contracting dipole gives the appearance of pulling lines together, manifesting a 'necking' effect rather akin to blowing a set of concentric bubbles.

After half period we have reached the situation shown in Fig. 6e. Some of the lines have broken away as closed loops and are propagating outward constituting the radiation field.

Hertz derived these 'pictures' from his combination of Cartesian and polar solutions for the fields obtained from the retarded potential function π . Let us now consider their meaning, but using spherical polar co-ordinates to obtain the fields from π . We obtain:

$$\mathbf{H} = (0, 0, H_\phi)$$

where

$$H_\phi = \frac{\omega P_0 \sin \theta}{4\pi} \left[-\frac{1}{r} \frac{\omega}{c} \sin \omega \left(t - \frac{r}{c} \right) + \frac{\cos \omega \left(t - \frac{r}{c} \right)}{r^2} \right] \quad (5)$$

The second term is immediately recognised as the Biot-Savart law for current element $I_0 dl \cos \omega(t - (r/c))$. The first term falls off as $1/r$, and so its energy density falls off as $1/r^2$, and this is indeed the radiation field: we notice that this field is proportional to dI/dt or d^2P/dt^2 .

The electric field terms become

$$E_r = \frac{\omega P_0 \cos \theta}{2\pi\epsilon_0} \left[\frac{1}{r^2} \frac{1}{c} \cos \omega \left(t - \frac{r}{c} \right) + \frac{1}{r^3} \frac{1}{\omega} \times \sin \omega \left(t - \frac{r}{c} \right) \right] \quad (6)$$

$$E_\theta = \frac{\omega P_0 \sin \theta}{4\pi\epsilon_0} \left[-\frac{1}{r} \frac{\omega}{c^2} \sin \omega \left(t - \frac{r}{c} \right) + \frac{1}{r^2} \frac{1}{c} \times \cos \omega \left(t - \frac{r}{c} \right) + \frac{1}{r^3} \frac{1}{\omega} \sin \omega \left(t - \frac{r}{c} \right) \right] \quad (7)$$

It can readily be seen that only those component terms of E_θ and H_ϕ which are proportional to $1/r$ give nonzero time average of Poynting vector $\mathbf{E} \wedge \mathbf{H}$, and, as this is proportional to $\sin^2 \theta$, there is no radiation along the dipole axis, as shown by the Hertzian field pictures.

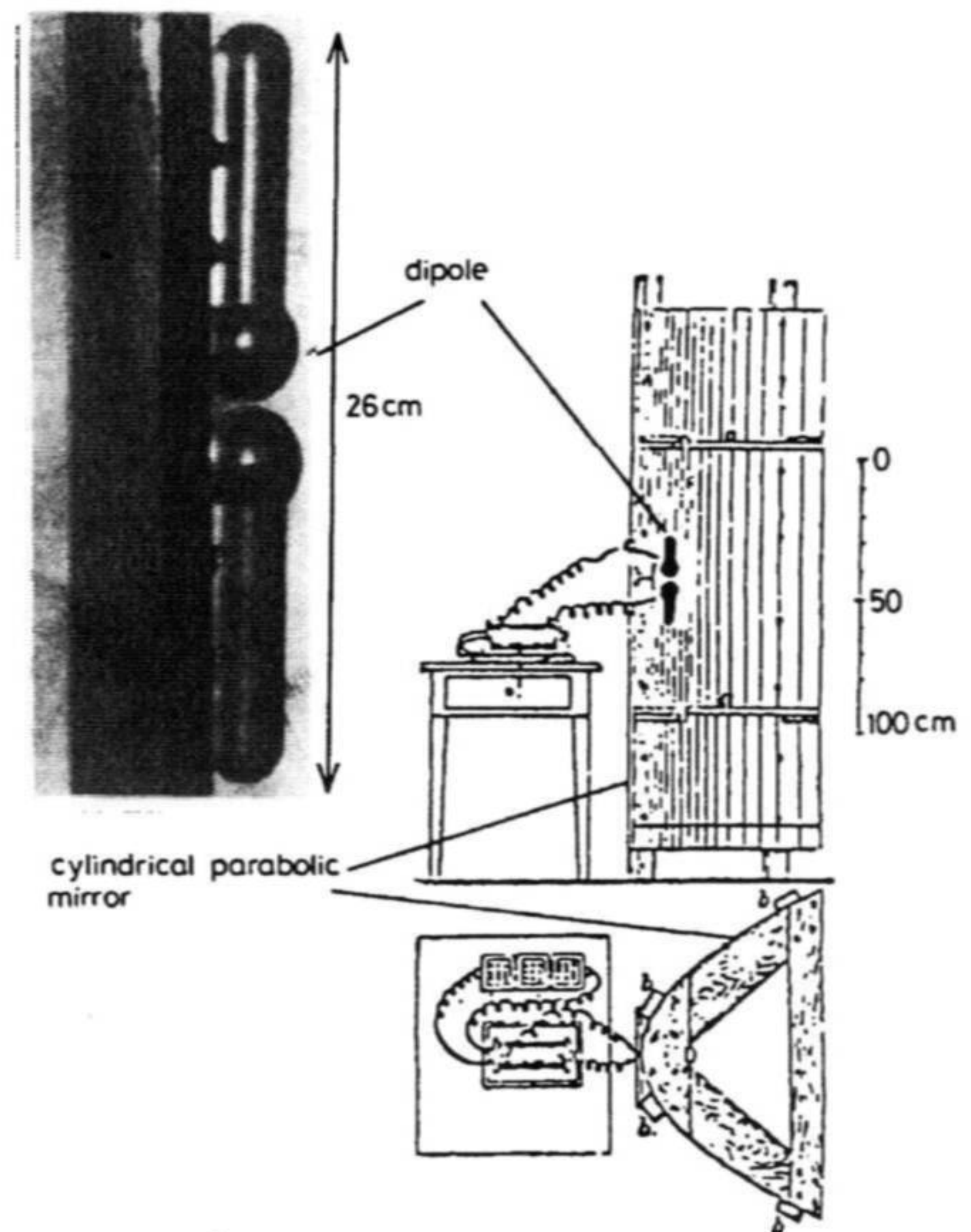
6 Hertz: the microwave optics pioneer

By demonstrating the optical properties of electromagnetic waves, Hertz won the applause of contemporaries who also sought to discover electromagnetic waves — notably Sir Oliver Lodge and D.E. Hughes.

With his sound knowledge of optics, Hertz realised the need to use wavelengths which were short, so that his optical aperture would be several wavelengths in diameter. His apparatus is shown in Fig. 7. He succeeded in generating waves of around 0.6 m wavelength with his invention of what we now call a halfwave dipole, excited by a spark gap at its centre and powered from an induction coil. He placed the dipole on the focal line of a metal parabolic cylindrical mirror, as shown in Fig. 7. For the receiver he used a nonresonant straight dipole placed on the focal line of another parabolic mirror. To ease the observation of the detector spark he passed leads from a gap in the centre of the detector dipole through insulated holes to the back of his mirror where the received radiation excited another spark gap.† With this apparatus Hertz demonstrated rectilinear propagation, polarisation, reflection and refraction, thus identifying the electromagnetic waves with much shorter light waves. Fig. 8 shows a photograph of the original reflectors which Hertz constructed at Karlsruhe.

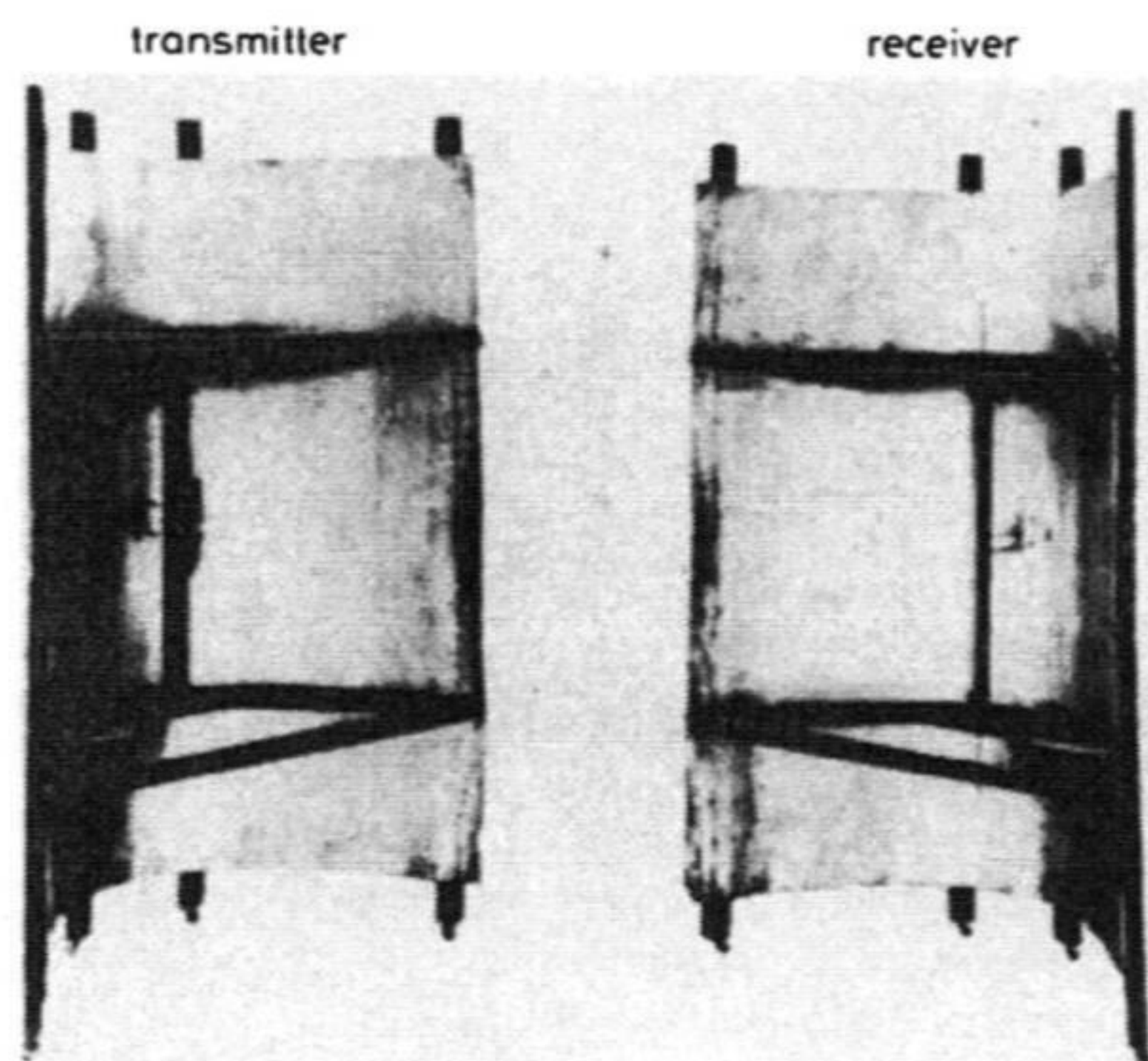
† Attempts to 'improve' on Hertz's spark gap detector were not without some comedy — H. Ritter successfully used a frog's leg! Professor Sir Augustus Abel at Woolwich Arsenal, employed explosive powder!

Using this apparatus, Hertz demonstrated that the beamed waves behaved almost like optical rays, with conducting



[Photograph: courtesy of Professor Wolfgang Paul]

Fig. 7 Hertz's original drawing of his quasi-optical radio transmitter with a close-up photograph of his spark transmitter dipole placed at the focal line of the parabolic reflector



[Photograph: courtesy of the Chancellor of Karlsruhe University]

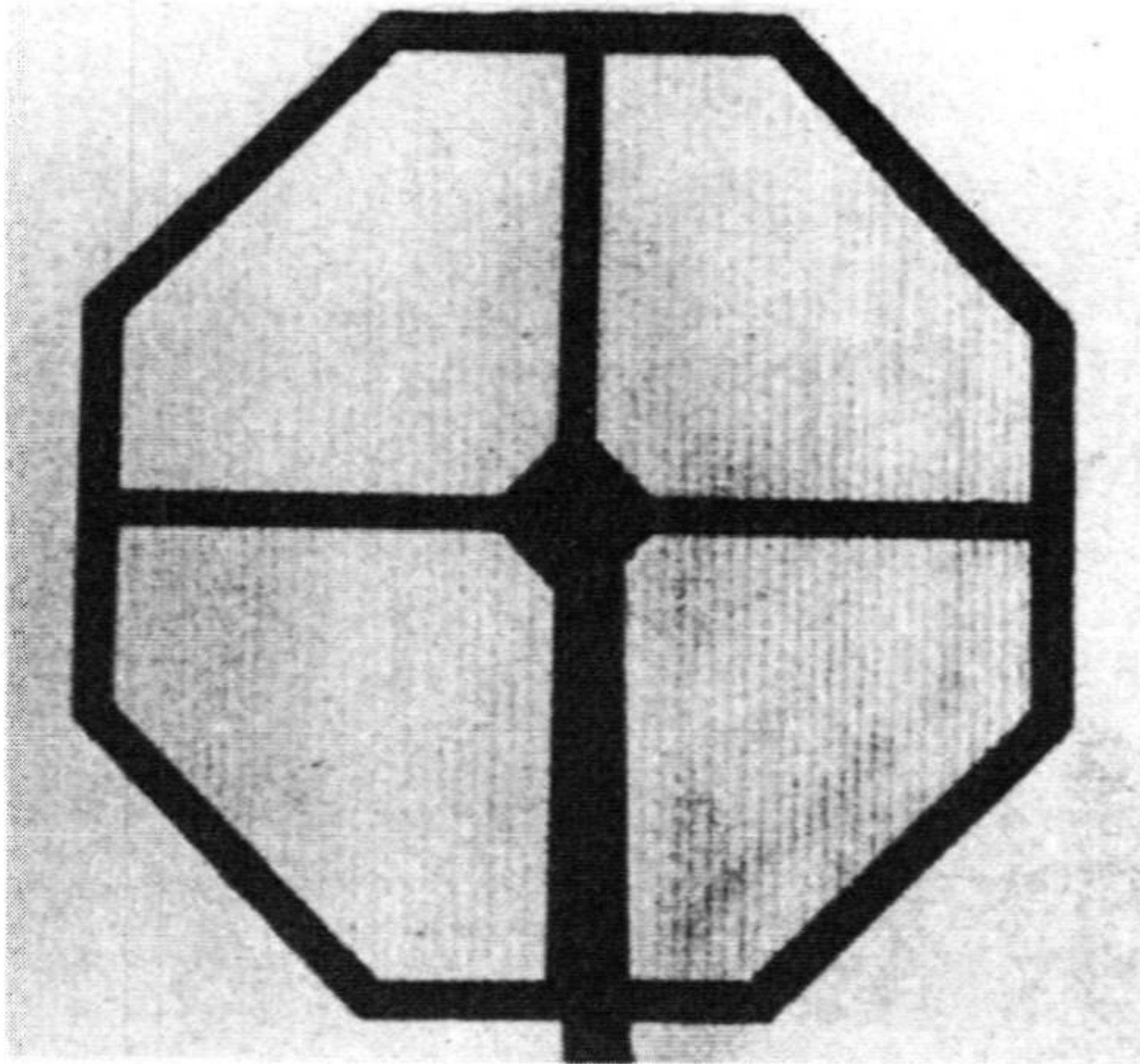
Fig. 8 Hertz placed his transmitter and receiver dipoles at the focal lines of these parabolic mirrors and demonstrated that electromagnetic waves obeyed the laws of optics

obstacles casting shadows. He demonstrated the transparency of insulators in accordance with Maxwell's theory and made the fascinating comment: 'Insulators do not stop the ray — it passes straight through a wooden partition or door; and it is not without astonishment that one sees sparks appear inside a closed room'.

The analysis of the radiation from Hertz's dipole had shown that the wave should be polarised with the electric field oscillating parallel to the dipole axis, i.e. at the equator of the dipole, and transverse to the ray path in accordance with Maxwell's equations. Hertz proved this

by experiment. He rotated the receiving mirror so that its focal line and receiving dipole were in the horizontal plane while the transmitter remained vertical. Hertz recorded: 'the secondary sparks became more and more feeble, and, when the two focal lines are at right angles, no sparks whatever are obtained even if the mirrors are moved close up to one another'.

Next Hertz arranged the construction of a wooden frame of 2 m diameter, across which were stretched parallel copper wires 1 mm thick, spaced 3 cm apart. The original frame is shown in Fig. 9. Hertz reported: 'If the two



[Courtesy of Professor Wolfgang Paul]

Fig. 9 Hertz placed this wire grill between his transmitter and receiver to demonstrate the polarisation of electromagnetic waves

(parabolic) mirrors were now set up with their focal lines parallel, and the wire screen was interposed perpendicularly to the ray and so that the direction of the wires was perpendicular to the direction of the focal lines (and hence perpendicular to the wave field electric vector), the screen practically did not interfere with the secondary sparks. But, if the screen was set up in such a way that its wires were parallel to the focal lines, it stopped the ray completely.' With these and other experiments Hertz identified polarised radio waves with polarised light, where the wire grill was acting as a polarising screen for the radio waves.

The laws of reflection and refraction were demonstrated by Hertz to be obeyed by radio waves just as in the well known examples of light waves. By ingenious manipulation of his loop detector Hertz demonstrated that, in a standing wave caused by normal reflection, the orthogonal electric and magnetic wave fields were in quadrature phase in space (i.e. where there was an electric node, there was a magnetic antinode, and vice-versa). His experiments with reflecting mirrors at various angles not only corresponded perfectly with optics but also established the principle of radar in all its electromagnetic essentials, thus making superfluous the debates about who really invented radar in the 1930s. Hertz described all the main types of reflection. Hertz's spectacular demonstration of the refraction of radio waves by a huge prism of asphalt-like pitch inspired Sir Oliver Lodge to construct the first radio-wave lens to focus the waves, in 1889.

The significance of these discoveries was summarised beautifully by Hertz himself: 'The experiments described appear to me, at any rate, eminently adapted to remove

any doubt as to the identity of light, radiant heat, and electromagnetic wave motion'.

It is simply astonishing how much of radio and radar technology was anticipated, generations in advance, by Hertz in his experiments. He even discovered the slow waves on a helix — the principle of the travelling-wave tube which Rudi Kompfner successfully invented at Birmingham University during the early 1940s, despite all the doubters of this principle! [16]

Perhaps the most fitting tribute to the work of Heinrich Hertz was paid in 1932 when the International Electrotechnical Commission, meeting in Paris, named the unit of frequency as the hertz with the symbol Hz.

7 D.E. Hughes 1830–1890

Numerous experimenters before Hertz had reported responses to electrical discharges at considerable distances; even including Galvani and Volta during their original experiments with frogs' legs in the previous century. Although few of the later workers enjoyed the mathematical and scientific prowess which enabled Hertz to identify the electromagnetic waves in accordance with Maxwell's theory, we mention, in particular, David Edward Hughes who carried out experiments in 1879, just a few years after Bell's invention of the telephone.

Hughes almost certainly observed effects which were due to electromagnetic radiation; namely the crackling sound in a telephone system when a spark discharge occurred in a remote inductive circuit some hundreds of metres away. However, Hughes could not convince Stokes that these effects were due to anything more than induction. Hughes was a considerable investigator in a highly skilled empirical way and he generously acknowledged the superiority of Hertz's identification of travelling waves, and their correspondence with Maxwell's electromagnetic theory of light. Of course the Hertzian dipole radiation fields, with their distinguishing $1/r$ dependence, were beyond the philosophy of Hughes.

8 Influence of Hertz on Randall

John Turton Randall, a Lancashire man, was born on the 23rd March 1905, at the small country town of Newton-le-Willows. His family background of nurserymen gave him an extensive knowledge of gardening which he put to great use in creating beautiful gardens from rough acres, throughout his life.

Randall studied physics at the University of Manchester, where he was prizeman. He graduated with top first class honours in 1925 and M.Sc. in 1926 after working under W.L. Bragg; the latter being, of course, famous for developing X-ray crystallographic analysis. For eleven years from 1926–37 Randall was an industrial research physicist with GEC, Wembley, engaged in X-ray diffraction analysis of amorphous materials such as glasses. These techniques were the precursors of his later studies in molecular biophysics. His industrial work also included improvements in materials for fluorescent lighting.

In 1937 he was awarded a Royal Society Warren Research Fellowship of the Cavendish Laboratory, Cambridge, but based at Birmingham University. In this appointment he pioneered research (with M.H.F. Wilkins) on solid-state luminescence, long before it aroused the widespread interest which it now attracts.

In fact, Randall described how his interest in microwaves did not arise at Birmingham until 1939, when it became 'painfully obvious' that the war was about to



[Courtesy of Christopher Randall]

Fig. 10 John Randall circa 1939 during his early assignment to the Isle of Wight radar station

begin. Two years previously, Oliphant had been appointed as the Poynting Professor of Physics at Birmingham, with plans for a nuclear physics laboratory and a 60 inch (1.5 m) cyclotron. Those plans were shelved in 1939. Oliphant involved himself with Cockroft, Appleton, Tizard and Watson-Watt and acquainted the British Nationals in his Birmingham team with the most secret chain of radar stations along the east and south coasts, see Fig. 10.

8.1 The cavity magnetron

The next part of the story is so fascinating that we surely cannot do better than read Sir John Randall's own account which he wrote in a letter to the present author, 9th April 1984, describing how the joint invention with Henry Boot led to the modern cavity magnetron:

'I was interested to learn of the article you are preparing on Heinrich Hertz. I naturally know less about Rudolph Kompfner and Erwin Schrödinger than I do about Boot and Randall.

In 1939 we had a flat in Aberystwyth which we used for holidays and which was a prospective place to which my wife and small son might go as and when war began. In July 1939 we were spending a short holiday there and I already knew from the activities of John Cockroft and Watson-Watt that groups of physicists from various universities, including Birmingham, were to pay visits to the long wavelength radar stations established on our south and east coasts by Watson-Watt and his colleagues. These visits were to last several weeks, the object being to acquaint us with the operation of radar at a wavelength of approximately 11 m. The "obscure" bookshop you mention was not in the least obscure and was in effect the

University College bookshop in Aberystwyth and went under the name of Galloway. Browsing in this shop one day I found a copy of Jones's translation[‡] of Hertz's "Electric waves" which I acquired with some interest in view of our coming radar activities. At that time no thoughts of magnetrons of any kind had occurred to me, but the use by Hertz of small rings of wire each with a short gap as detectors of his electric waves stuck in my mind. Boot was in no way concerned with this. I was in charge of the Birmingham team at the Ventnor Radar Station for, if I remember correctly, about 6 weeks. For some reason I cannot now recall, Boot and I were left behind for a week or two after the rest of the Birmingham team had returned to base. Most of the scientists involved were assigned to work on the use of the klystron in "radiolocation" systems. When Boot and I eventually returned to Birmingham the more interesting tasks had been assigned and we were left with the task of discovering whether a Barkhausen-Kurtz tube could be used as a detector. After several weeks experiments in the corner of a large teaching lab we decided that this was not possible. Boot and I worked very closely together both then and throughout my subsequent stay in Birmingham which terminated in the autumn of 1943. Consequently, during this early comparatively leisurely period in 1939 we were isolated from the main stream of activity in the lab and had plenty of opportunity to discuss the problem of short wave transmitters and particularly whether the klystron as it then was could produce the power required to give a satisfactory early-warning system. We concluded, as history shows, that it would not be sufficiently powerful.

An important factor should be recorded at this point. The whole lab was buzzing with talk of resonators and particularly of the Hansen papers. This naturally had a great influence on Boot and me as well as other members of the team; and we have always fully acknowledged that the atmosphere in which we worked influenced the direction of our thoughts. The only device we were able to think of which could possibly combine the desired attributes of resonators and high power output was a magnetron. We were well aware of modifications that had taken place in magnetron construction during the pre-War years particularly at the GEC Wembley; General Electric in Schenechedy and also in Germany. As a former colleague of E.C.S. Megaw at the Research Laboratories of the GEC, Wembley, I was aware of his activities in this field.

However, none of these magnetron devices was satisfactory from our point of view, since they did not embody truly enclosed resonators and consequently showed marked frequency-pulling on load. It was at this stage that I thought of the cylindrical extension of a Hertzian dipole** and Boot and I jointly tested the system of 6 such resonators clustered round and facing into the anode-cathode space. We presumed that there would be strong electromagnetic coupling between the different resonators and therefore inserted a coupling loop so that power could be withdrawn from one resonator only.

There was very little suitable equipment in Birmingham at this time since Oliphant had only recently taken up the Poynting Professorship of Physics. We managed to borrow a suitable transformer from ASE at Portsmouth; made our own mercury rectifiers and found an old large Biot electromagnet suited to our purposes. We had the idea of the cavity magnetron in November 1939 and we

[‡] The English translator of Hertz's 'Electric waves' was D.E. Jones who had been Professor of Physics at Aberystwyth — M.J.L.

** Sir John is referring here, of course, to a dipole loop — M.J.L.

showed the first copper block to Bragg and Appleton when they paid a visit to the lab during that month.

The first experiments with the magnetron "on the pump" were carried out on February 23, 1940, and we were astonished to see streams of (high frequency) radiation coming from the output wire attached to the coupling loop. We had no ready means of measuring the power, but made attempts by decapping car headlamps of increasing wattage and hanging the filament lead on the coupling loop. In all cases the lamps were burnt out. This was a C.W. system as no modulators were as yet in existence and we later established that our first valve produced about 400 Watt, $\lambda \approx 9.8$ cm.'

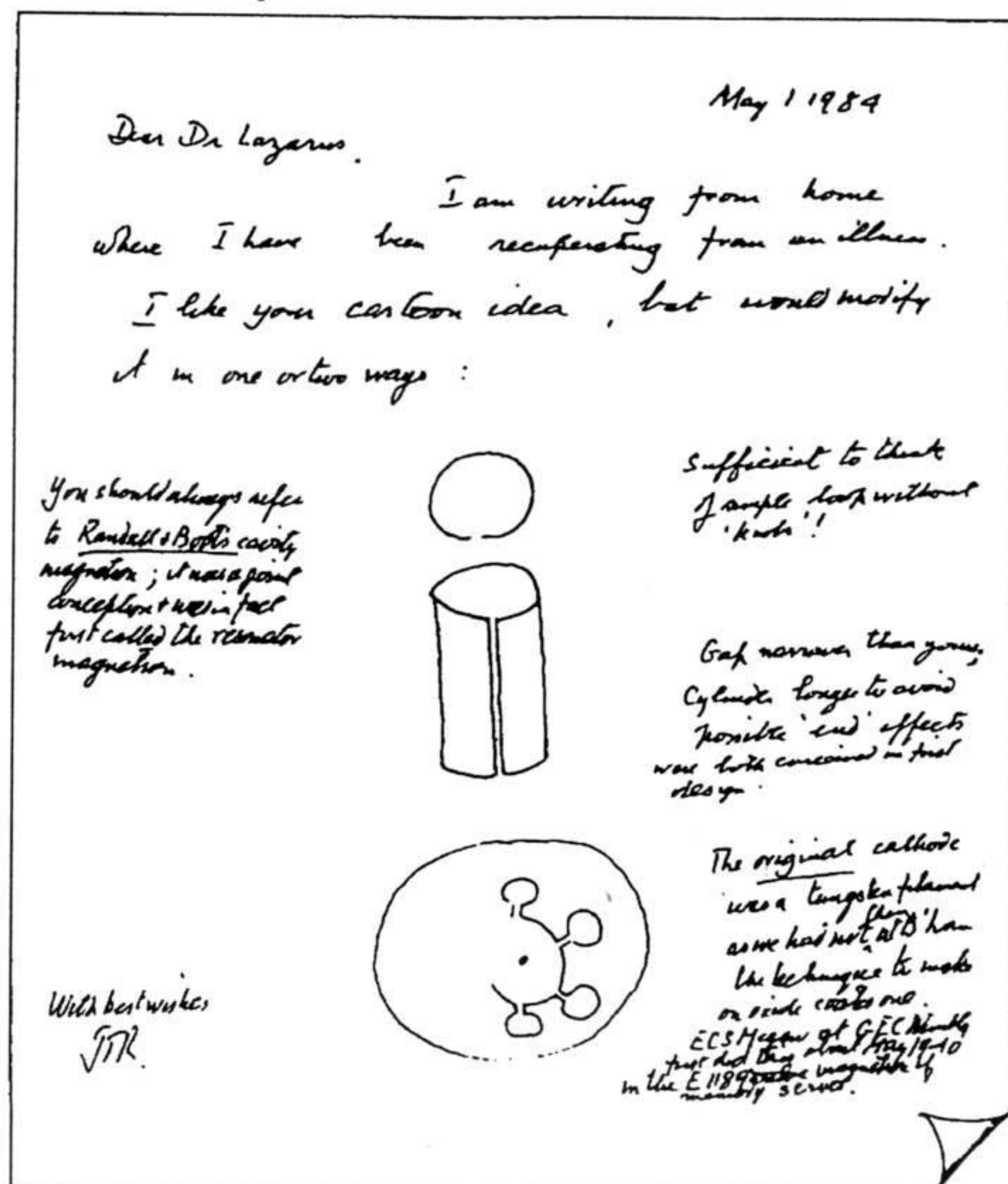
In a further letter, dated 12th April 1984, Sir John Randall described the theoretical basis on which he and Henry Boot made the calculations of the wavelength of the oscillations from their magnetron:

'I am very pleased that you found my letter helpful for your article. You may certainly quote extracts from it concerning the influence of Hertz if you think they are well enough expressed.

There is an old book by H.M. Macdonald, Professor of Mathematics at Aberdeen University in the earlier part of this century. I think the title is "Electric waves". In this book he calculates the wavelength of radiation to be expected from a Hertzian dipole of diameter d and finds the value, if my memory is correct, of $7.98 d$. As you know, the observed wavelength of our first block turned out to be 9.8 cm. This was measured a few days after the first operation by a simple Lecher wire system employing a small neon lamp.'

The 'old book by H.M. Macdonald' was in fact the published edition (Cambridge University Press, 1902) of an Adam's Prize Essay written by the Cambridge mathematician H.M. Macdonald F.R.S., with the expressed purpose of analysing Hertz's experiments. For a Hertzian loop dipole resonator of diameter d Macdonald calculated a wavelength $\lambda = 7.95 d$ which indeed agreed closely with experiment for $d = 12$ mm in the first cavity magnetron.

Sir John Randall's final letter describes, so vividly, with cartoon sketches, his train of thought, that we cannot do better than reproduce it here.



9 From sealing wax to mass production

The equipment problems in that wartime research were severe. Randall described how it was necessary to create home-made continuously pumped high-voltage rectifiers for the power supply. The magnetron itself was continuously pumped with vacuum seals made from sealing wax. Despite these difficulties his sense of humour prevailed, and he described how the magnetron generated powerful oscillations 'on the morning when all of this equipment operated simultaneously'. No power meters were available, so the power was estimated by using the microwaves to burn out filament lamps, and in this way several hundred watts were confirmed. Wavemeters, likewise, were not available and several days of measurements with Lecher lines were necessary to determine the wavelength, which was 9.8 cm.

By contrast with the pioneering work with sealing wax, industrial development of a rugged portable device, with high-current oxide-coated cathode, was extremely rapid, notably with the aid of E.C.S. Megaw and S.M. Duke of G.E.C., Wembley. Impressive 10 kW pulses at 10 cm wavelength were soon achieved. A radar operating at 10 cm was in operation by May. Following the famous scientific mission to President Roosevelt in the USA, the 10 cm magnetron was demonstrated at Bell Laboratories in October 1940. By November, 1940, Bell Laboratories had supplied working copies of the British magnetron to the radar research teams at MIT.

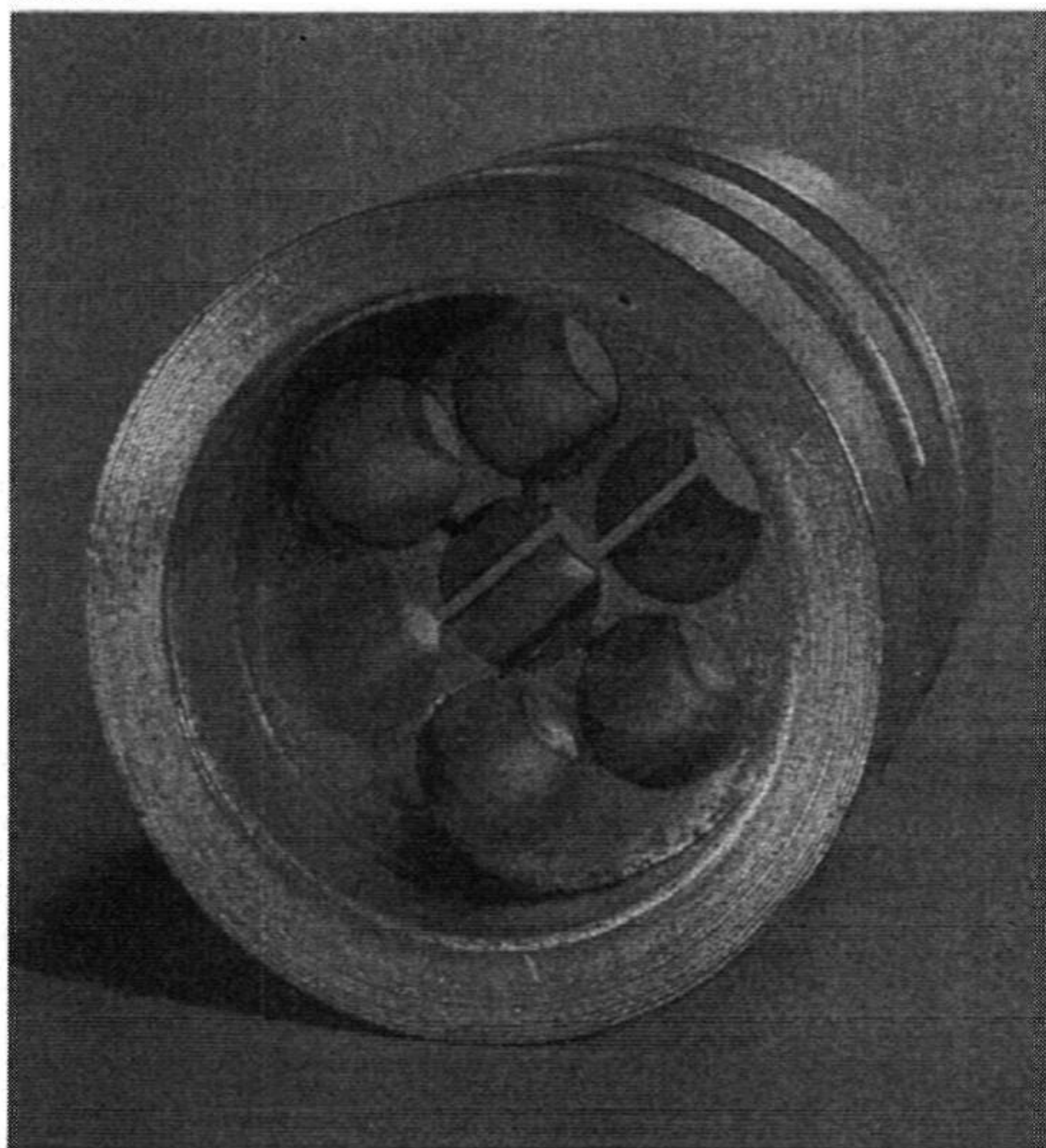
Of the various improvements to the cavity magnetron, perhaps the most notable was that of 'strapping' developed by Sayers at Birmingham. Copper bars or straps were introduced to connect cavities so that only the desired so-called π -mode would predominate in the system of coupled resonators. In this way considerable increase in power at a single frequency was obtained.

Many hundreds of thousands of cavity magnetrons were produced during the War, and without them, the U-boats might well have succeeded in cutting off Britain's supplies. There is probably no other single invention which had such a crucial effect on the outcome of the Second World War.

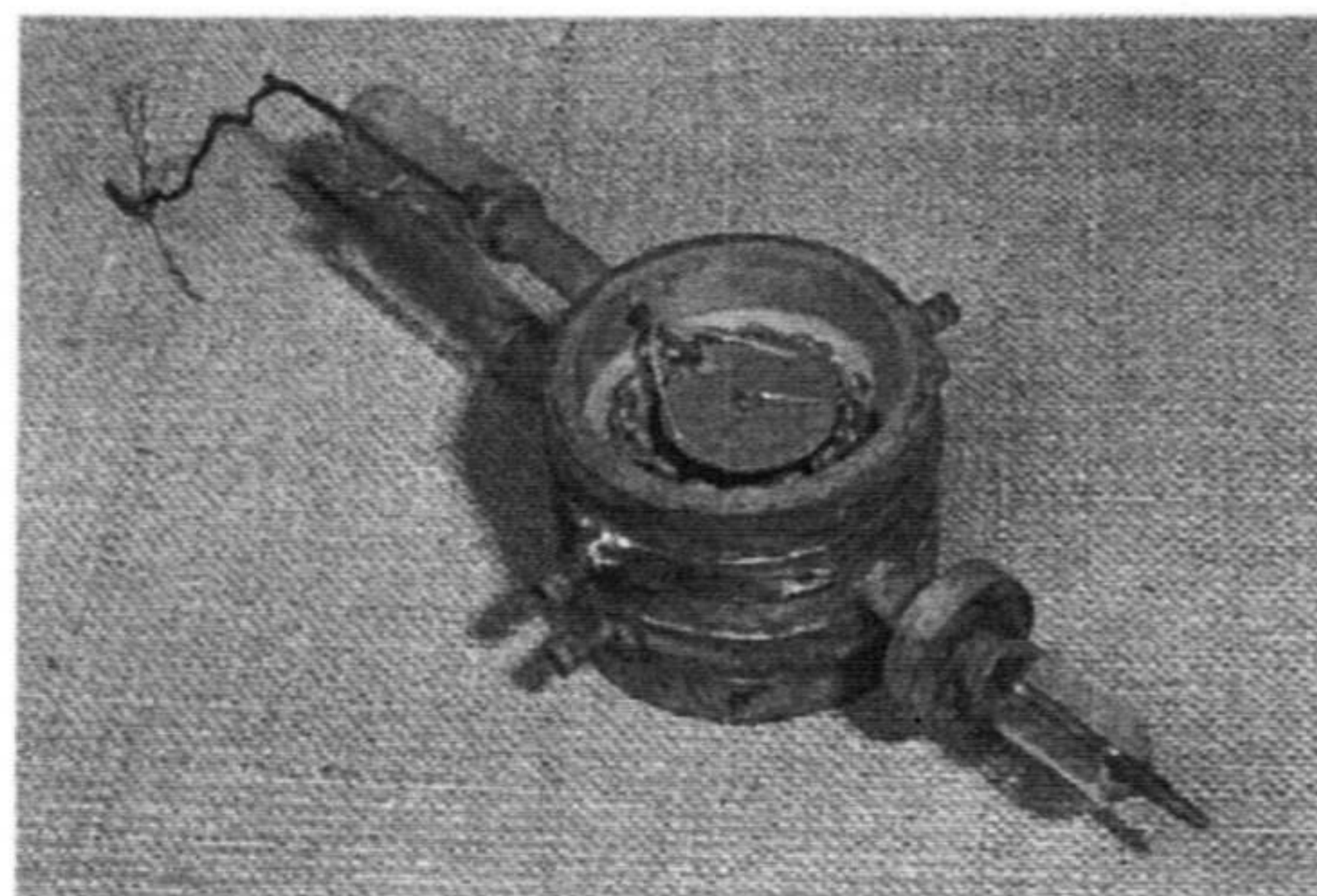
The cavity magnetron success attracted some of the most distinguished mathematical physicists of the time to its further study. In England D.R. Hartree derived relationships between the required voltages and magnetic fields which are still in use today. In the USA, J.C. Slater analysed many of the conditions of operation and his book 'Microwave electronics' is a classic in the field, and still well worth reading.

Many other modes of operation of cavity magnetrons have been identified since the pioneer work of Boot and Randall. In some of these, the mechanism is more akin to a 'rolled up' travelling tube with the slot cavities acting as slow-wave structures. For shorter wavelengths where the small cavities would make strapping very difficult, an alternative to the clover leaf cluster of cavities was developed using radial 'rising sun' slots cut from the anode block. By alternating the depths of these slots, it is possible to select the π -mode. Nevertheless, the original clover-leaf cavity clusters of Boot and Randall are still widely used, and, for example, for 3 cm wavelength, these are now available in tunable form with an adjustable tuning plunger inserted into one of the cavities to perturb the frequency of the coupled system. The present day long-life rugged magnetrons have, of course, resulted from extensive research in metallurgy, ceramics, and cathode materials, and moreover we must not forget the ingenuity of the magnetic materials scientists whose discoveries have provided tiny but

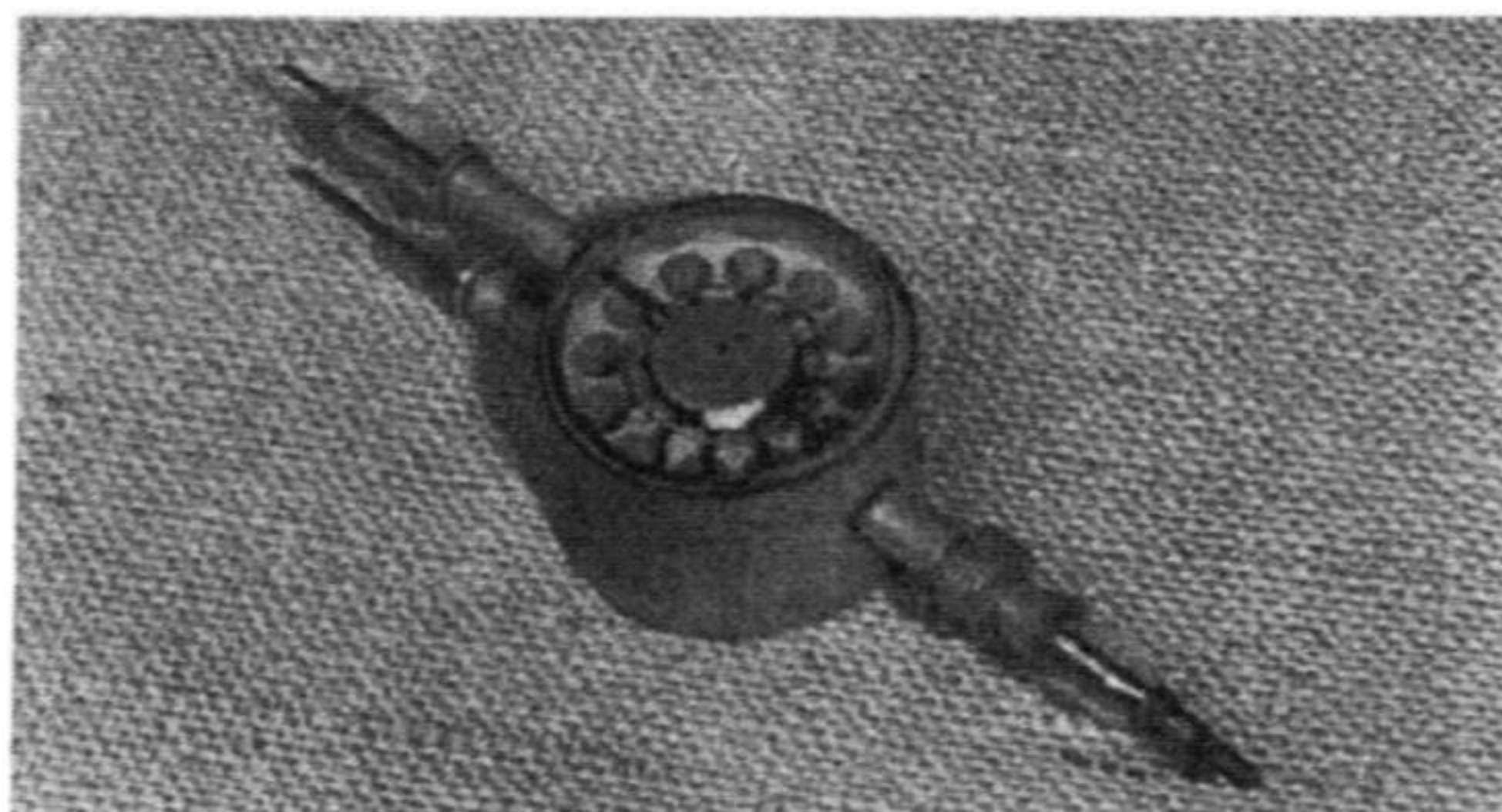
extremely powerful permanent magnets for modern magnetrons.



[Courtesy of the Science Museum, South Kensington, London]
Fig. 11 Original cavity magnetron block of Randall and Boot
 Actual size



a



b

[Courtesy of Birmingham University Physics Department]
Fig. 12 Subsequent developments of multicavity magnetrons made by Randall, Boot & Sayers at Birmingham University

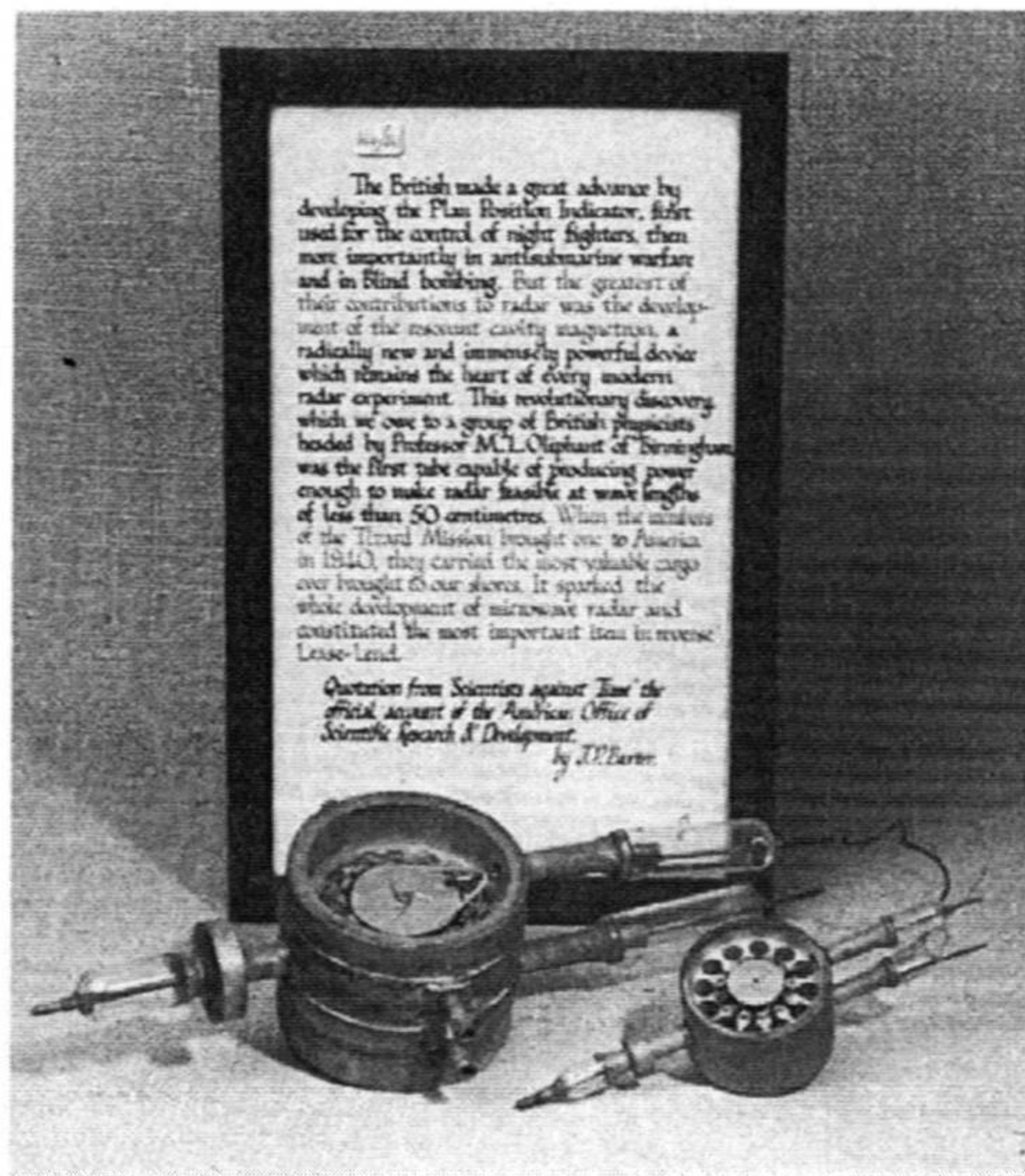


Fig. 13 American accolade

10 From microwaves to molecular biophysics

Randall remained at Birmingham until 1943 developing higher frequency magnetrons, almost to millimetric wavelengths. He was then a lecturer at the Cavendish Laboratory, in Cambridge, until 1944 when he was appointed Professor at St. Andrews University, Scotland, where he remained for two years. In 1946 he was elected to the F.R.S. and appointed Wheatstone Professor of Physics at King's College, London. Distinguished honours, too long to list, were awarded to him for his wartime work with Boot and Sayers — but already he was developing new fields. Randall's profound contributions to many branches of science were recognised by a knighthood in 1962.

Skills in science and organisation enabled Randall to build up research teams in molecular biophysics which rapidly became world-famous. He originated many applications of modern physics to biology, and these were introduced to both research and teaching.

It is now common knowledge that deoxyribonucleic acid (DNA) is the genetic material of life. Yet, long before this was confirmed and the double helix of the DNA molecule was discovered, Randall pointed, in 1946, to DNA as the molecule involved in growth and composition of the gene carriers in the cells — the chromosomes.

In Randall's laboratory many famous personalities used his X-ray diffraction equipment in the molecular structural analysis of DNA. This work eventually led to the identification of the double helix, for which a Nobel prize was shared by M.H.F. Wilkins with Watson and Crick of Cambridge.

Notwithstanding his supreme eminence as both a scientist and an administrator, Professor Sir John Randall, F.R.S., delighted to remain a friendly companion for people at all levels. He was frequently to be seen experimenting enthusiastically into the night or chatting with youngsters in the laboratory, and was active as a scientist almost until his very last days.

11 Dr. H.A.H. Boot 1917–1983

Henry Albert Howard Boot, better known to everyone as 'Harry' Boot, was born on the 29th July 1917. He attended King Edward's High School, Birmingham, and then Birmingham University where he was a scholar, graduating with B.Sc. in 1938 and Ph.D. in 1941. He became renowned for his skill in making difficult apparatus work, and he had already won the respect and admiration of his colleagues (especially Randall) during his time as a young research student. He spent the period 1939–1945 in research on cavity magnetrons developing them to extremely high power levels, and won numerous prizes, medals and awards. After a period as a Nuffield Research Fellow at Birmingham he joined the Royal Naval Scientific Service at SERL, Baldock, in 1948. His interests in high-power electrodynamics led him into research on plasma physics and optical masers (lasers).

Harry (Henry) Boot loved to play jokes on people. One of his pranks was to spread a story that the first cavity magnetron block was the rotating part of a six shooter! His sense of fun resembled the impish wit of Maxwell and Heaviside.

It is befitting to the humorous homeliness which characterised both Boot and Randall that, today, countless millions of cavity magnetrons are manufactured for microwave cookers.

Although solid-state devices, especially MOS power transistors, have now invaded the last stronghold of thermionics, one device which will almost certainly survive is the cavity magnetron in view of its small size, superb efficiency and immense power. It will always be associated with one of this century's greatest applied scientists, namely 'Harry' Boot.

12 Salutare!

The recent death of Sir John Randall was almost coincident with the centenary of the work of another Olympian of science — Heinrich Hertz. Many tributes have been made to both of these supreme innovators, and yet anyone who studies their contributions will quickly feel that no superlatives are adequate to give accolade for their works. There was a link between these two great minds and the present writer has here endeavoured to impart the descriptions, which he had the privilege to receive recently from Sir John, explaining how the discoveries made by Hertz of radio waves (and microwaves) included techniques which led to the invention of the cavity magnetron and microwave radar of unprecedented power and precision.

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