Microwave energy generation advances which enabled the development of WWII airborne radar.

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(with Simon Watts and John Thompson)

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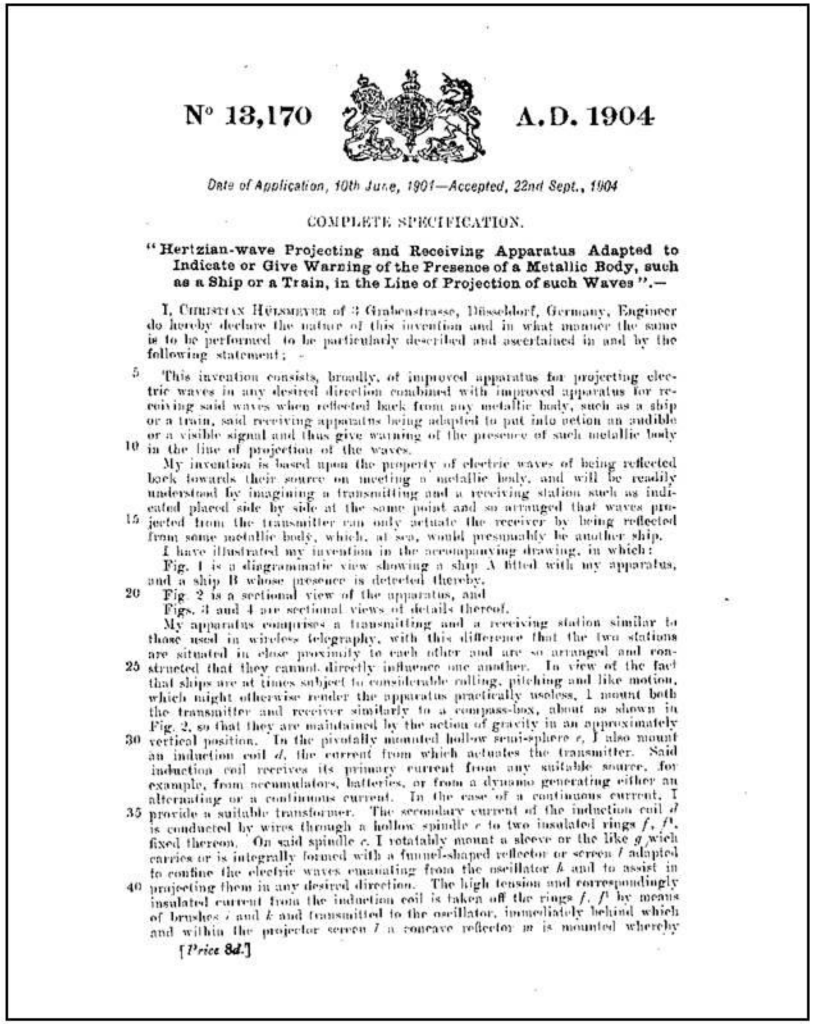
Why am I talking about Airborne Radar?

IEEE President, Tom Coughlin, congratulating me at Birmingham in June 2024.

Overview

- Early British radar and microwaves
- Cavity Magnetron development before 1939
- The Birmingham initial technical advances
- GEC significant technical enhancements
- The Tizard Mission to the US
- Improving the frequency stability
- UK & US wartime airborne radar systems
- Recognition for the inventors

Hülsmeyer UK patent: 10 June 1904



N° 13,170 A.D. 1904

Date of Application, 10th June, 1901—Accepted, 22nd Sept., 1904

COMPLETE SPECIFICATION.

"Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as a Ship or a Train, in the Line of Projection of such Waves".—

I, Christian Hülsmeyer of 3 Grabenstrasse, Düsseldorf, Germany, Engineer do hereby declare the nature of this invention and in what manner the same is to be performed to be particularly described and ascertained in and by the following statement:—

This invention consists, broadly, of improved apparatus for projecting electric waves in any desired direction combined with improved apparatus for receiving said waves when reflected back from any metallic body, such as a ship or a train, said receiving apparatus being adapted to put into action an audible or a visible signal and thus give warning of the presence of such metallic body in the line of projection of the waves.

My invention is based upon the property of electric waves of being reflected back towards their source on meeting a metallic body, and will be readily understood by imagining a transmitting and a receiving station such as indicated placed side by side at the same point and so arranged that waves projected from the transmitter can only actuate the receiver by being reflected from some metallic body, which, at sea, would presumably be another ship.

I have illustrated my invention in the accompanying drawing, in which:

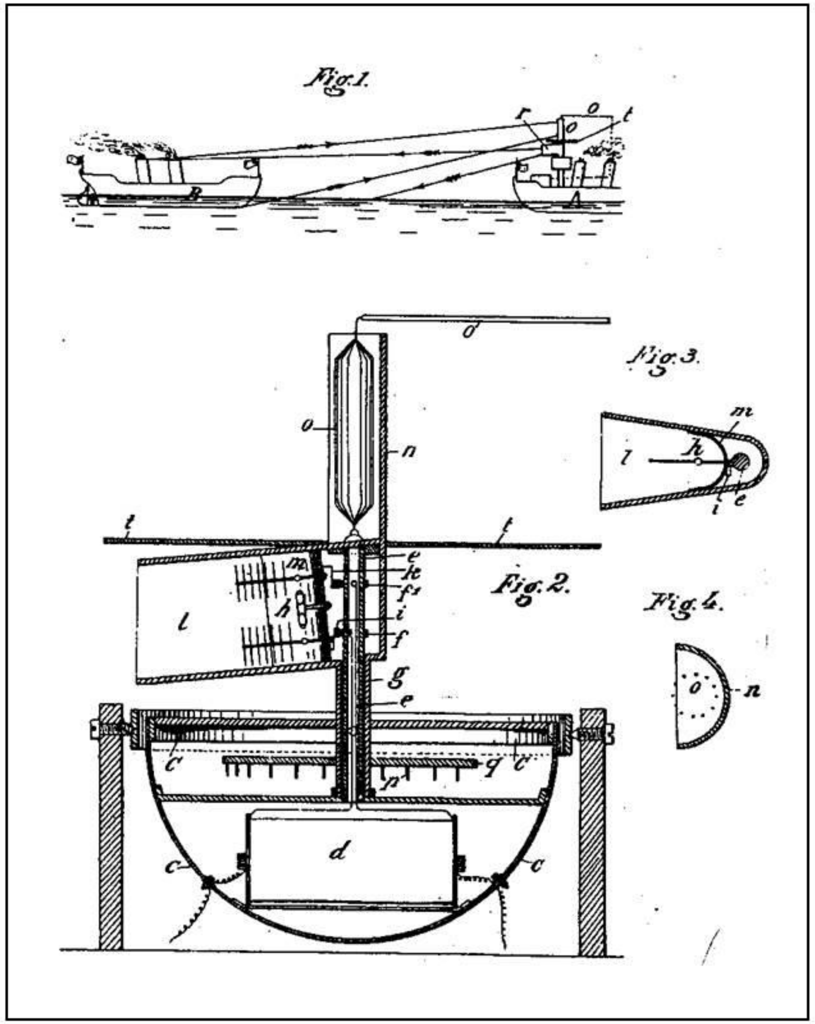
Fig. 1 is a diagrammatic view showing a ship A fitted with my apparatus, and a ship B whose presence is detected thereby.

Fig. 2 is a sectional view of the apparatus, and

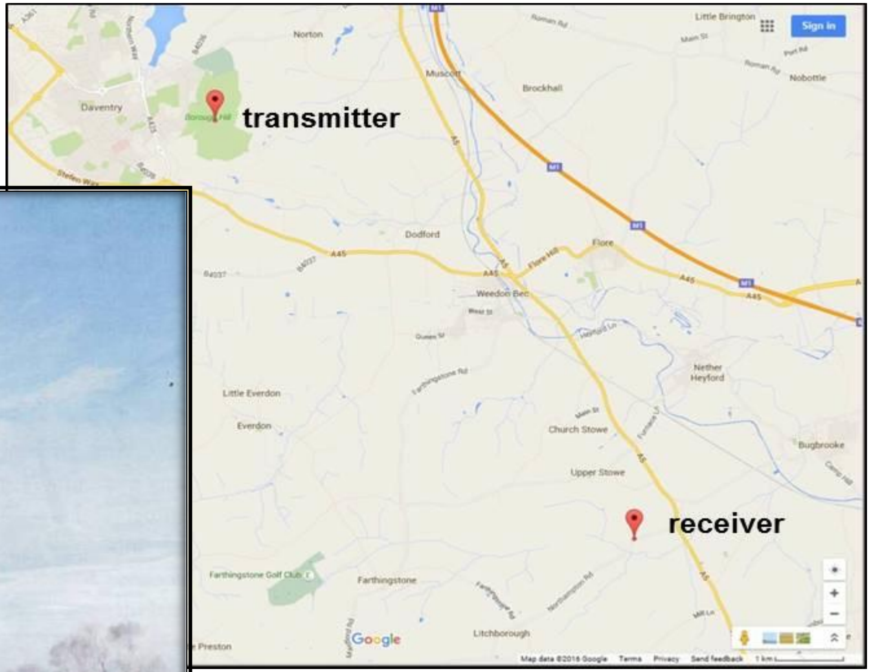
Figs. 3 and 4 are sectional views of details thereof.

My apparatus comprises a transmitting and a receiving station similar to those used in wireless telegraphy, with this difference that the two stations are situated in close proximity to each other and are so arranged and constructed that they cannot directly influence one another. In view of the fact that ships are at times subject to considerable rolling, pitching and like motion, which might otherwise render the apparatus practically useless, I mount both the transmitter and receiver similarly to a compass-box, about as shown in Fig. 2, so that they are maintained by the action of gravity in an approximately vertical position. In the pivotally mounted hollow semi-sphere *c*, I also mount an induction coil *d*, the current from which actuates the transmitter. Said induction coil receives its primary current from any suitable source, for example, from accumulators, batteries, or from a dynamo generating either an alternating or a continuous current. In the case of a continuous current, I provide a suitable transformer. The secondary current of the induction coil *d* is conducted by wires through a hollow spindle *e* to two insulated rings *f*, *f*[1], fixed thereon. On said spindle *e*, I rotatably mount a sleeve or the like *g* wich carries or is integrally formed with a funnel-shaped reflector or screen *l* adapted to confine the electric waves emanating from the oscillator *h* and to assist in projecting them in any desired direction. The high tension and correspondingly insulated current from the induction coil is taken off the rings *f*, *f*[1] by means of brushes *i* and *k* and transmitted to the oscillator, immediately behind which and within the projector screen *l* a concave reflector *m* is mounted whereby

[*Price 8d.*]



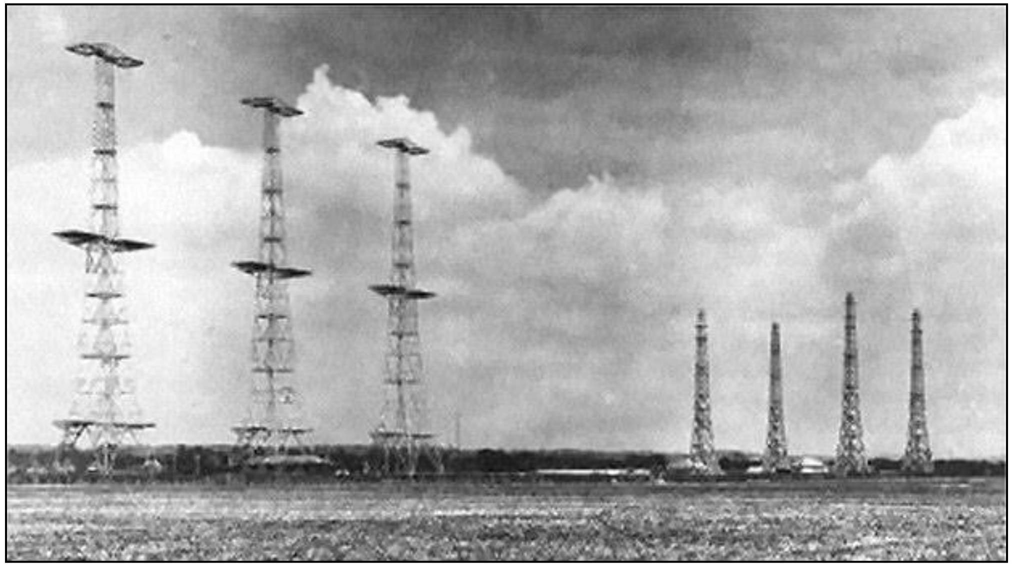
The Daventry Experiment: 26 February 1935

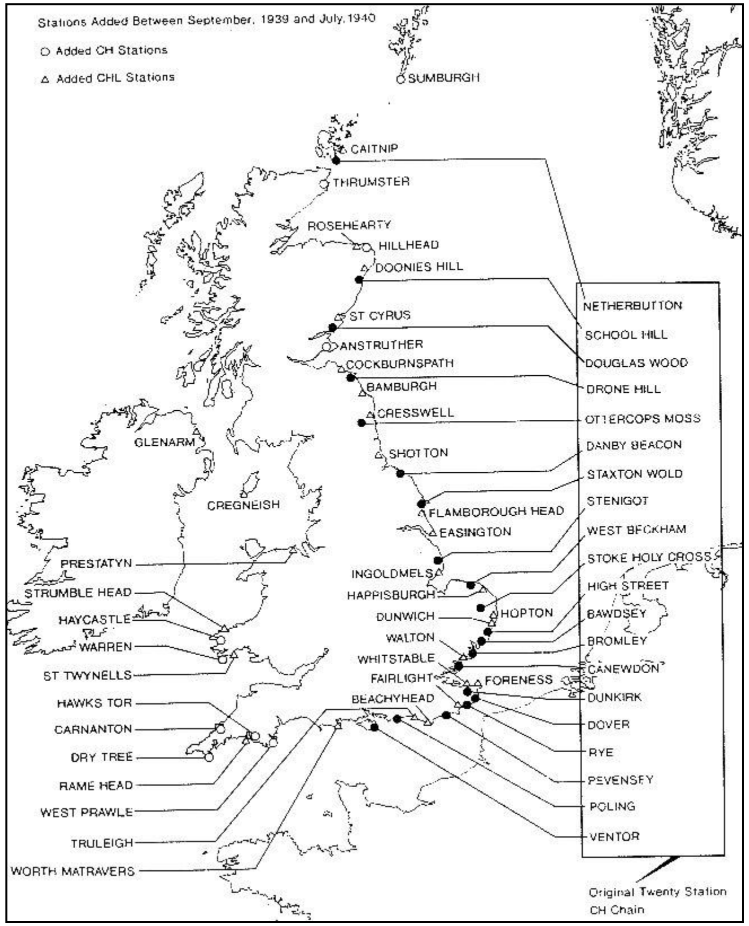


Painting by Roy Huxley

Robert Watson-Watt, detected the presence of an aircraft using reflected radio waves.

Chain Home radar system





1939 land based early warning radar
operated at 20-50 MHz.

Neale, B.T., 'CH – the First Operational Radar', *GEC Journal of Research*, Vol. 3 No.2 pp73-83, 1985.

Robert Watson-Watt's Memorial statue

Watson-Watt who was born in Brechin, studied at the then University College in Dundee.

During WW II he became Scientific Advisor on Telecommunications to the Ministry for Aircraft Production, travelling to the US in to advise them on the inadequacies of their air defence systems.

Knighted in 1942 and buried in Pitlochry.

As the father of UK radar his Brechin memorial shows him with Chain Home in one hand and an aircraft in the other.

Image Wikipedia

Airborne radar

Pre WW II airborne military surveillance radar was for RAF Coastal Command and the Fleet Air Arm. Air to Surface Vessel (**ASV**) systems operated at a somewhat higher (176 MHz) frequency.

AI (Airborne Intercept) radars were installed on night fighters and to aid the accuracy of bomber ordinance delivery.

These airborne radars required still higher microwave frequencies, with centimetre wavelengths, to reduce the size of practical radar systems, **enabling them to fit into an airframe.**

Further, GHz frequencies provide superior resolution of targets for **bomb aiming**, **long range night-fighter and anti-submarine systems**.

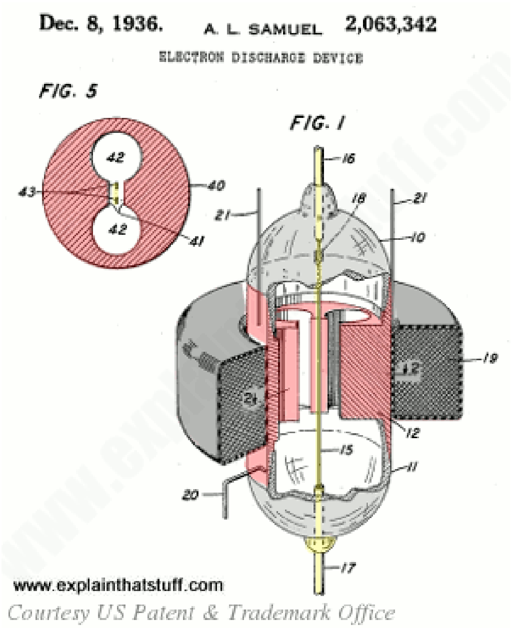
Mk II ASV antennae

Me 110 antennae

Images from Wikipedia and RAF Museum

The Magnetron

The magnetron **generates microwaves from the interaction of a stream of electrons with a magnetic field while moving past a resonator**



Early design lacked a satisfactory method of coupling the resonators to the load.

The magnetron name originated from work by **Albert Hull** in 1921 at GE Schenectady in New York.

Cavity Magnetron development before 1939

In the 1930s, the British expert on magnetron design was Eric Megaw at GEC who published reviews, including split-anode magnetron designs.

Many of the previous international designs were not built as prototypes and practical devices were limited to a generally a modest 10 W power output.

Nowhere in the world **in 1939** was there a **working, pulsed, *cavity magnetron*** capable of **generating 10 kW or more peak power at wavelengths of 10 cm or less**, which had a **compact portable size**, used a **small permanent magnet** and which was readily capable of being **manufactured at scale**.

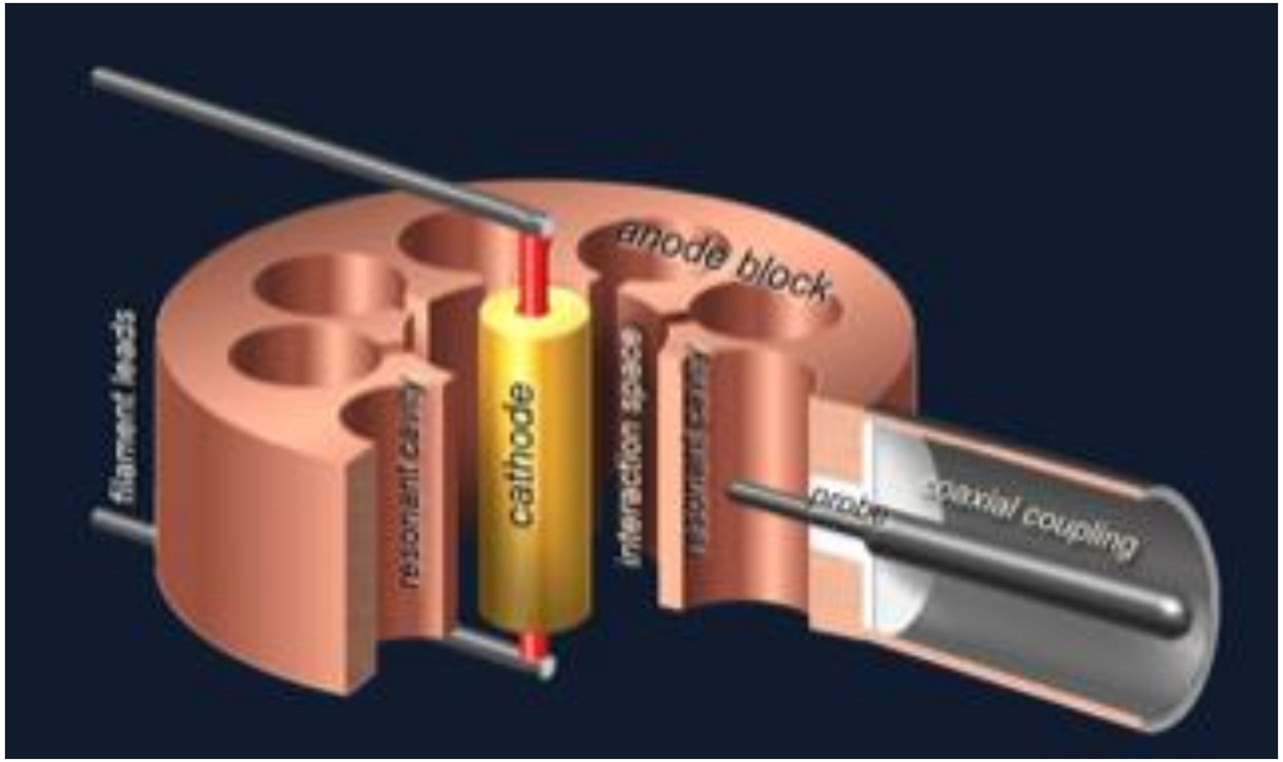
Marcus Oliphant led an Admiralty funded research group at Birmingham University working on radar system design, whose team made the initial advances.

Diprose 2015 Yorkshire IET Radio/Radar lecture. DEFENCE ELECTRONICS HISTORY SOCIETY Vol 22 No 3, Sept 2017

John Randall and Harry Boot later in 1975

Norman Fine from MIT Technology Review, Oct 2024

Birmingham Cavity Resonator



The anode block of an early cavity magnetron showing the initial 6 & later 8 cavity resonators

The Birmingham technical advances

Randall and Boot showed their first copper resonator block to **Lawrence Bragg and Edward Appleton** during their visit in November 1939.

The precise dimensions of the 6 cylindrical resonator geometry, with slots parallel to the cathode axis, controlled the generated frequency.

The first device, sealed in wax and permanently connected to a vacuum pump, generated on 21 Feb 1940, 400 W of continuous wave output at 10 cm or 3 GHz, lighting a neon lamp.

Birmingham innovation removed the glass envelope with the **vacuum system inside the anode structure** to achieve **more efficient anode cooling** and, with the induction coupling loop inside the cavity, it permitted the higher dissipation to **generate the increased in microwave power**.

This was **the major technological 1940 revolution** making the **novel, innovative steps which paved the way for further technical advances in next generation of future magnetron devices** at the appropriate time to assist the war effort.

doi: 10.1109/T-ED.1976.18476

The First Birmingham Prototype

They replaced previous glass envelope by a copper resonator.

The device is sandwiched between two square water cooled plates and image shows the resonator detail.

This academic device had wax seals but needed a pump to maintain the vacuum and it required an external electromagnet for the required large magnetic field.

Courtesy London Science Museum

Birmingham Electromagnet

Courtesy University of Birmingham

Some comments on the innovation

Randall had bought a copy of a translation of Heinrich Hertz's "*Electric Waves".*
Boot and Randall claimed that, from this, they researched the design of the original Hertz open single ring oscillator.

H.M. Macdonald had published as part of his 1901 Cambridge Adam's Prize essay a description of his mathematical analysis of Hertz's experiments. To generate radiation at 10 cm wavelength Macdonald showed that the resonator diameter requires to be 12 mm as the resonant wavelength of Hertz's wire loop resonator was 7.94 times its diameter.

This so called "Hertz related development" (which might have been adopted to assist with their patent claims) is disputed by some researchers who believe the cylindrical resonant cavity concept would have been be known to Oliphant through his work on the klystron!

We do know that the Hansen papers were available in the Birmingham laboratory, but these designs could not be readily associated with the desired cylindrical cavity symmetry.

10.1049/ji-3a-1.1946.0183

Further Engineering Enhancements

In April 1940, the Admiralty signed a contract with GEC Wembley to produce an operational magnetron with neither vacuum pump nor an external magnetic field generator.

The GEC group was led by **Eric Megaw** who was an established expert on conventional magnetron design.

He incorporated several technical enhancements into his GEC cavity magnetron to increase the output power and improve the device lifetime.

Photo after IEEE AP Magazine 2013

Birmingham - GEC interactions

Randall had worked at GEC on luminescence before moving to Birmingham in 1937.

There were clearly technical meetings held between GEC staff and the University researchers.

Considerable assistance on sealing glass to copper and, for joining copper to copper with gold wire under pressure, was received at Birmingham from **S. M. Duke**, a member of the GEC Wembley staff, who later joined the Birmingham group in June 1940.

Development beyond the Academic Device

Megaw had 5 years of magnetron collaborations, with French engineers.
Ponte brought to Wembley on 6 May 1940 samples of Henri Gutton's "M16 (cm)" device which had an oxide coated cathode for improved power and lifetime.

The GEC engineers, deployed industrial practice to improve the design of the Birmingham vacuum seals and thus remove the pump requirement transforming the Birmingham design into a **sealed-off version.**

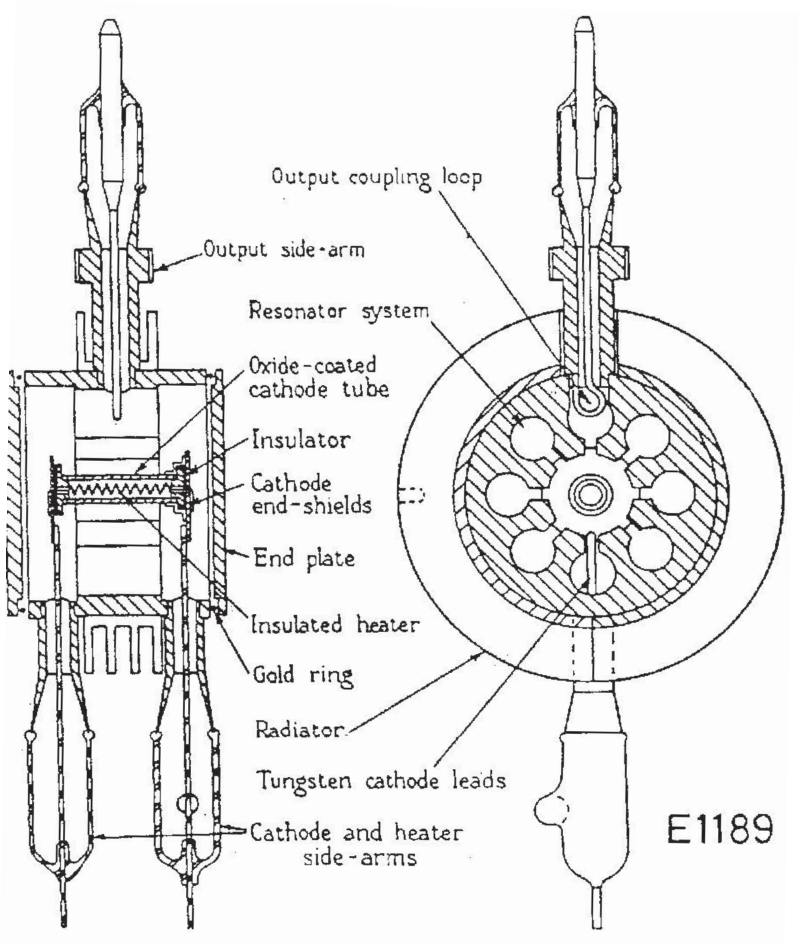
Finally they combined the Birmingham multi-resonator system with a large oxide coated cathode to construct the NT98 device with a **permanent** magnet, to improve lifetime and enable manufacture in quantity.

These innovations enabled the pulsed power output to be progressively improved to 3 kW then 10 kW, within months to 25 kW!

Maurice Ponte

M16 Magnetron

GEC E-1189 Magnetron



E-1189-2 or b with an oxide coated cathode and changed aspect ratio increased power to 15 kW with improved lifespan. By 1941 power further increased to over 100 kW with 65% efficiency.

In September 1940 at Telecommunications Research Lab, Swanage, a land based T/R system detected a surfaced submarine at 11 km distance.

This was all achieved in 3 months under wartime conditions!
Bleneim flight trials followed in March 1941.

Image Radio Museum Lucerne, Switzerland & IEEE AP Magazine 2013

1940 GB Patent 588,185 RANDALL, BOOT and WRIGHT published in 1947

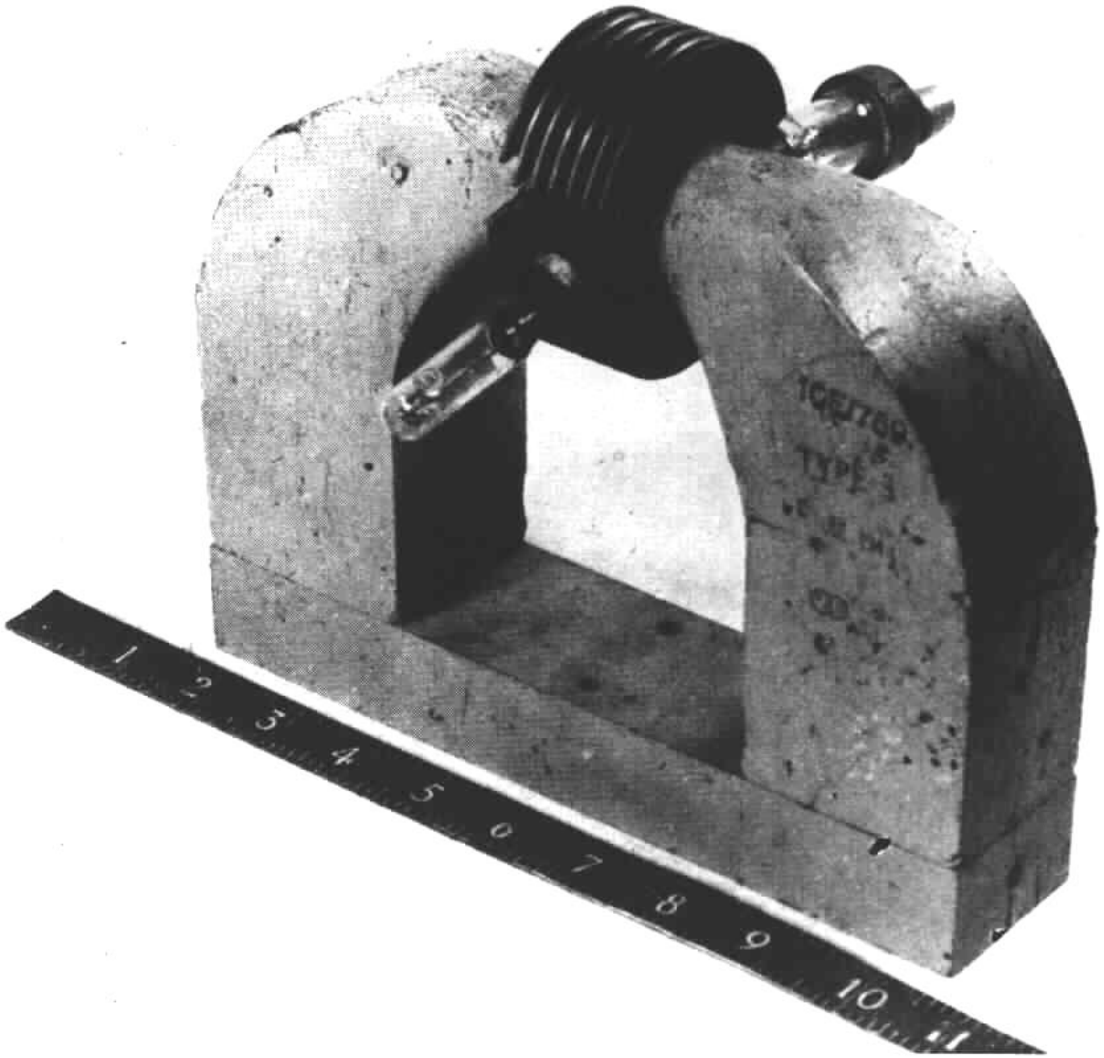
In a magnetron for the generation of continuous or interrupted wave oscillations a number of **resonant chambers** are formed in a block of tellurium copper alloy.

The resonators are connected by **narrow passages to a central chamber** in which is mounted a cathode.

The resonators and chamber communicating with side chambers are formed by copper discs which close the sides of the block.

(Interestingly the figures in **Randall and Boot** 1953 US Patent 2,648,028 include the GEC E-1189 magnetron design details and it reports on the oxide coated cathode design but **Megaw** is not named as one of the inventors!)

GEC E-1189 reduced axial dimension Magnetron with permanent magnet



Navy used first cavity magnetron radar

Recall the Admiralty sponsored this R&D.

Type 271 naval radar was used in corvettes for anti submarine operations.

This used the first NT98 5 kW magnetrons.

HMS Orchis began sea rials in the Clyde in March 1941.

First naval radar system to detect targets even if they were very close to the horizon!

Over 150 of these equipments were built.

Image Wikipedia

Naval cavity magnetron radar II

In larger ships, the reduced wave movement, enabled the deployment of a mechanical stabilizer to overcome the pitch and roll.

5 months later in August 1941 photo shows Type 273 radar on cruiser *HMS Nigeria*.

It deploys the cheesebox antennae, shown above the bridge.

On a 36 foot high mast, the radar can track a surfaced submarine at 5,000 yards.

Image Wikipedia

The September 1940 Tizard Mission

As Britain lacked the funding and manufacturing capability, Churchill arranged **for** Henry Tizard to offer the magnetron design to the Americans in exchange for financial and industrial help.

At the September 1940 meeting the US Navy representatives detailed the problems with their short-wavelength systems, complaining that their klystrons could only produce 10 W.

Edward (Taffy) Bowen, a British radar engineer, pulled out from his briefcase the E-1189-12 8 cavity magnetron and explained that it could already produce 1000 times that power.

A meeting report stated: "*The atmosphere was electric - the US experts found it hard to believe that such a small device could produce so much power, and that what lay on the table in front of us might prove to be the salvation of the Allied cause*".

Tizard Mission thus initiated parallel radar development in Britain and America.

Mission also contained a Birmingham memo with the first calculations on the critical mass of material for an atomic bomb, concluding that it was small enough to be delivered by aircraft!

Tizard Mission follow on

In the 1930's American radar was developed in Universities, companies and financier **Alfred Loomis** in his private New York Tower House laboratory.

America formed the **National** MIT Radiation Laboratory to build magnetron radar systems in parallel with the British efforts.

Standing: **Lee DuBridge** MIT Rad Lab director, on right **Isaac Rabi** magnetron team leader, while **Taffy Bowen** (seated) explains the magnetron operation.

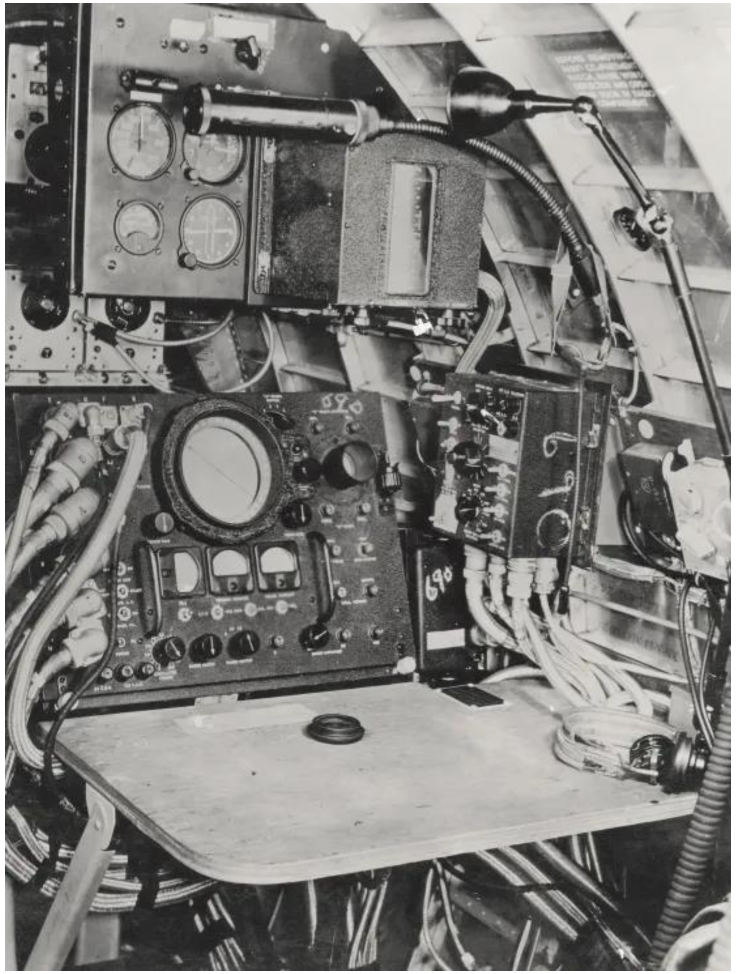
Image MIT Museum

MIT radar development

The MIT Radiation Laboratory then built US magnetron based radar systems.

7 February 1941 MIT land based radar mounted on lab roof detected aircraft at 2 mile range.

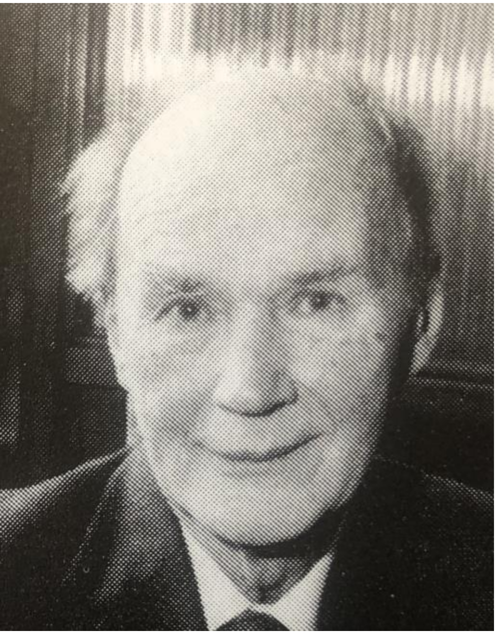
First flight trial on 7 March in a Douglas B18 bomber (flying with Bowen) detected ships at 10 mile range and a submarine at 4 miles.



Later MIT handbuilt radar system

Image MIT Technology Review

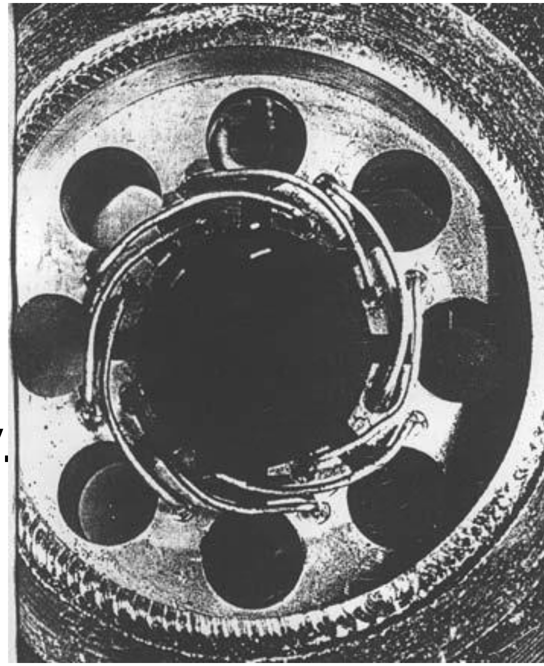
The Birmingham later follow on



James Sayers had designed, at Birmingham, a 10kV centimetric wave klystron.

In July 1941 he *improved the frequency stability* of the cavity magnetron design.

He **“strapped”** alternate cavities to alleviate mode hopping and generate only a single output frequency.



Strapping doubled or trebled the power output!

His strapped magnetron became the CV64 device.

Figures from University of Birmingham and TRE report T 1858

Magnetron based centimetric airborne radar

Airborne radar requires centimetre wavelength transmissions,
for long range night-fighter and anti-submarine systems.

Higher operating frequency provides the superior target resolution for munitions delivery.

The scanned antennae focusses the beam and enables a map display.

The first centimetric Airborne radars used British built magnetrons!

Early 1942 Airborne Interception (AI) radar used the British CV64 magnetron.

The ASV Mk. III sea-surface search submarine detector in a Wellington mounted the scanner in the teardrop fairing under the nose.

Radar scanner with a waveguide feed and reflector

Image Wikipedia

US Magnetron airborne bomb aiming radar

A fleet of 12 B-17 Flying Fortress bombers were fitted with 3 cm radar bombsights.

Designated H2X, the 12 MIT Radiation Lab hand built radars were installed at Boston Airport.

12 US pilots flew the B-17s to England, in late 1943.

During a bombing run, the rotating antenna was lowered from the chin of the fuselage.

The first production model H2X equipped B-17 was flown to England in January 1944.

Norman Fine from MIT Technology Review, Oct 2024

Magnetron based centimetric airborne radar

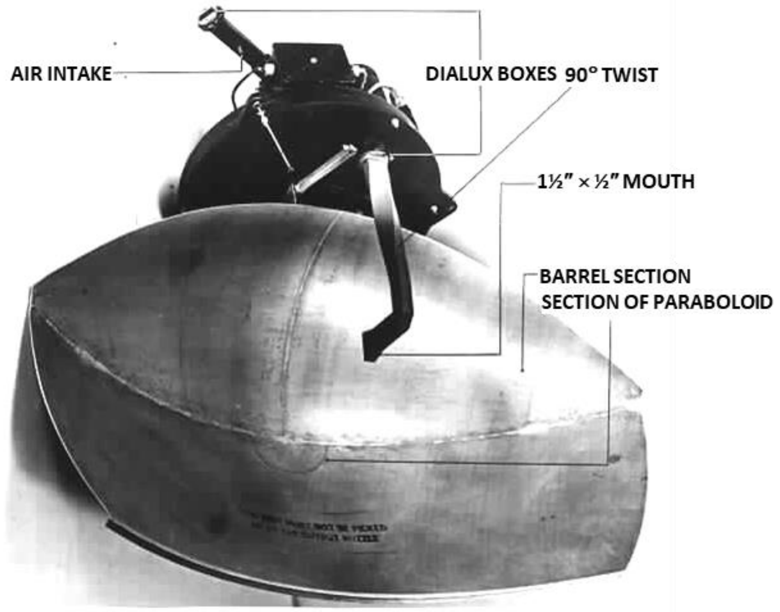
The ASV Mk. III British sea-surface search submarine detector used the strapped CV64 magnetron.

The most widely-deployed British magnetron radar was the H2S ground mapping bombing aid. H2S Mk. I, ~ 3 GHz, entered service in 1943.

H2S Mk. II was used for hunting U-boats, while they were surfaced for re-charging their batteries.

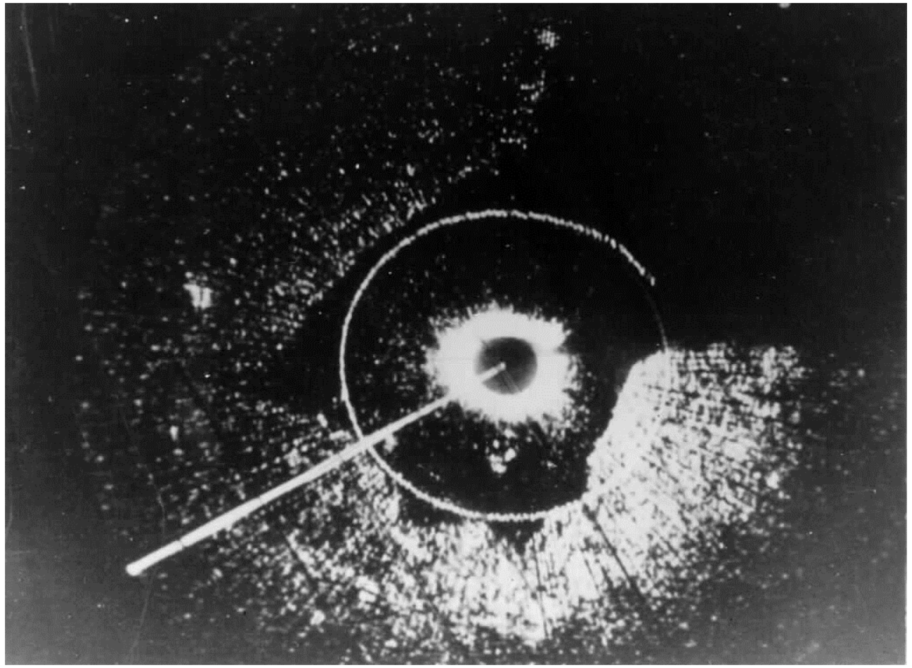
Boot claimed that, by 1945, some 250,000 magnetrons were delivered for British deployment??

H2S Mk. IX was finally used in 1982 by the Vulcan bombers that attacked Port Stanley during the Falklands War!



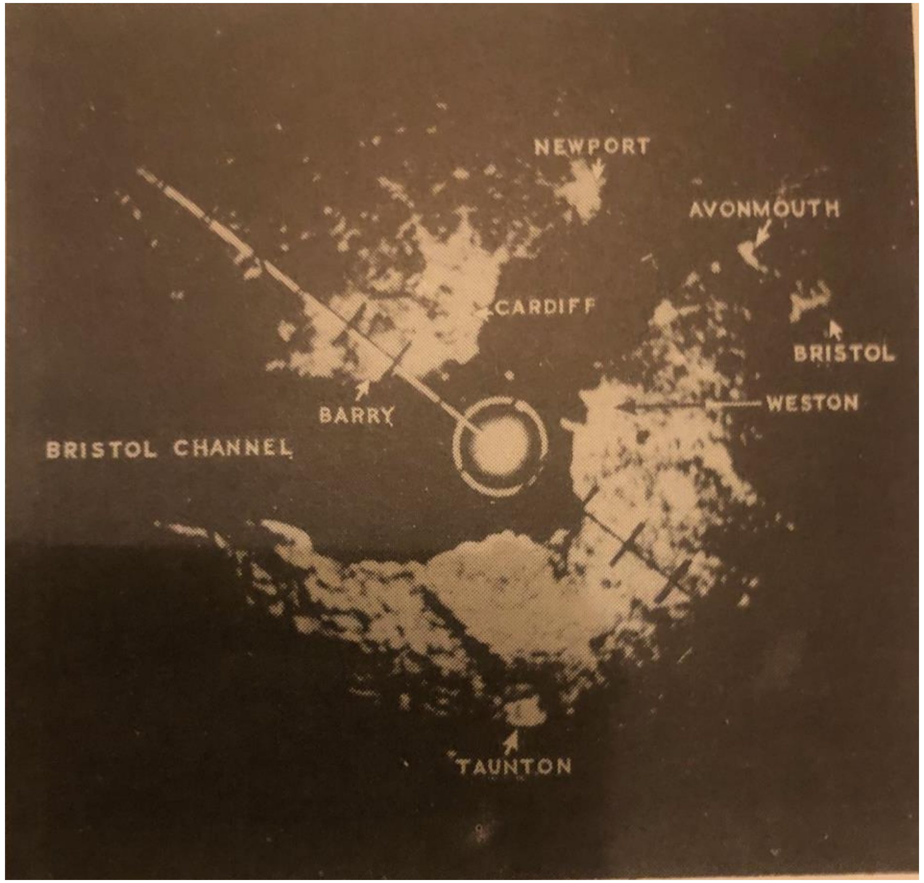
H2S Mk. III radar scanner (X-band) with 36″ aperture

Magnetron centimetric airborne radar image



Plan Position Indicator (PPI) display from WW 2 H2S Mk. III radar,
taken at an altitude of 18,000 feet, over the Wash in North East coast of England.

Magnetron centimetric airborne radar image



PPI display from WW 2 H2S radar, over the Bristol channel.
Key advantage is that radar can image through cloud!

Airborne radar pioneers memorial

Alan Blumlein of EMI, the inventor of stereo audio, was central to the development of the H2S airborne radar system. He died in Wales after a Halifax trials flight crash on 7 June 1942.

Bernard Lovell arrived to recover the secret magnetron with the crash then covered up during WW II.

A memorial window in Goodrich Castle in Herefordshire commemorates Blumlein and the other engineers, scientists and servicemen who were involved in WW2 radar development.

Note the cavity magnetron resonator at the top of the middle window.

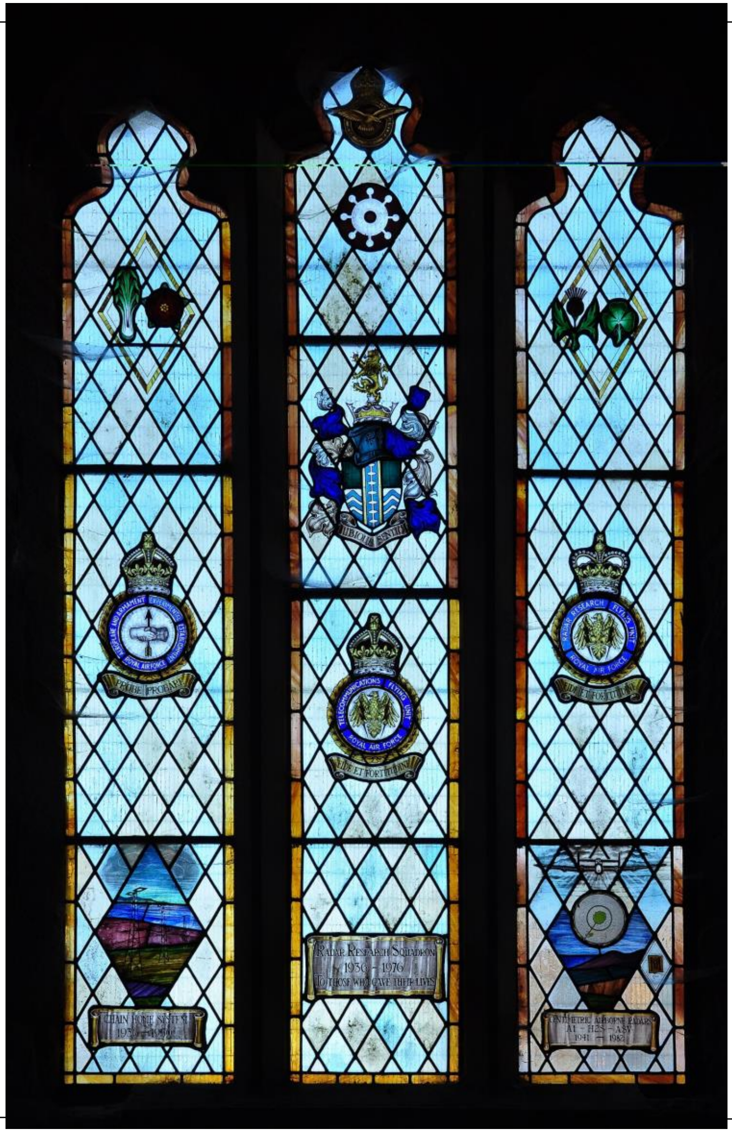


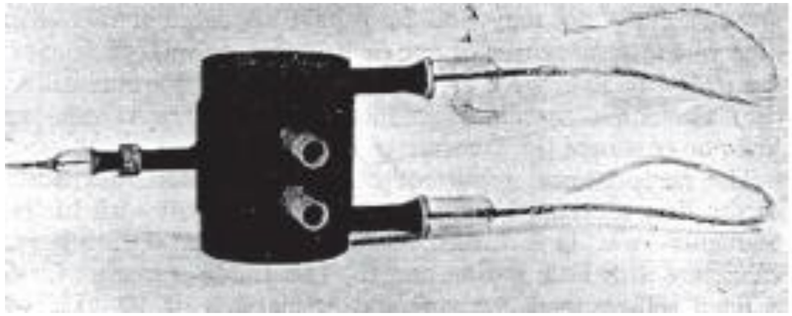
Image Wikipedia

Other parallel developments!

Nakajima's 1939 Japanese design of an eight-cavity "M3" magnetron generating 500 W output at 10 cm, preceded the Birmingham design.

Nakajima only discovered the E-1188 GEC device on his post-war April 1953 visit to the London Science Museum.

He noted: the Birmingham dimensions of the glass covering the vacuum; the anode water-cooling system; and the anode mechanism; were very similar to his own "M3" design.



E-1188 the first GEC Magnetron used a Birmingham resonator

doi 10.1098/rsnr.2004.0058

Russian Developments

Alekseev and Malairov's Russian cavity magnetron was well known at Telefunken during WW II!

Alekseev and Malairov had constructed a four-segment 300 W continuous wave cavity magnetron with a tungsten cathode operating at a wavelength of 9 cm (3.3 GHz) but this was **unknown** in England in 1939!

Alekseev and Malairov only published their results in Russian and German in 1940, (J. Tech Phys USSR 10, p.1297), repeated in English in JIERE later in 1944!

German radar

In February 1940 Reichsmarshal Hermann Göring had issued a “development stop order”, demanding concentration on developing longer wavelength rather than centimetric radar systems!

The cavity magnetron innovation was so sensitive that allied aircraft were not permitted to fly over Germany and explosives were deployed to destroy the magnetron if shot down.

In February 1943, a Stirling bomber with H2S radar crashed near Rotterdam, with the Germans finally acquiring the complete radar system details.

German engineers then copied the British CV64 magnetron as their “Nachbau” or LMS10 device.

Hachenberg’s 1943 German report on the aircraft crash, which was only discovered in 2001 after his death, confirmed that Telefunken engineers had known about Russian cavity magnetron design!

doi 10.1098/rsnr.2004.0058

Conclusion

We know in retrospect that Russian, Japanese and other scientists had also developed Cavity Magnetron designs but their results were not openly published prior to WW II.

Nowhere in the world **in 1939** was there a **working, pulsed, *cavity magnetron*** capable of **generating 10 kW or more peak power at wavelengths of 10 cm or less,** which had a **compact portable size**, used a **small permanent magnet** and which was readily capable of being **manufactured at scale**.

The British engineering design advances were progressively undertaken by Randall, Boot, Megaw and Sayers which enabled high performance airborne radar systems.

Luckily the axis governments failed to recognise the true significance of these advances!

Subsequent recognition

Randall, Boot and Sayers innovations were recognised with a 1949 "Royal Commission on Awards to Inventors" of £36,000, with further financial benefit arriving after lobbying by EEV.

David Zimmerman, Professor of military history in British Columbia stated:
"*The magnetron remains the essential radio tube for shortwave radio signals of all types. It not only changed the course of the war by allowing us to develop airborne radar systems, it remains the key piece of technology that lies at the heart of your microwave oven today. The cavity magnetron's invention changed the world*."

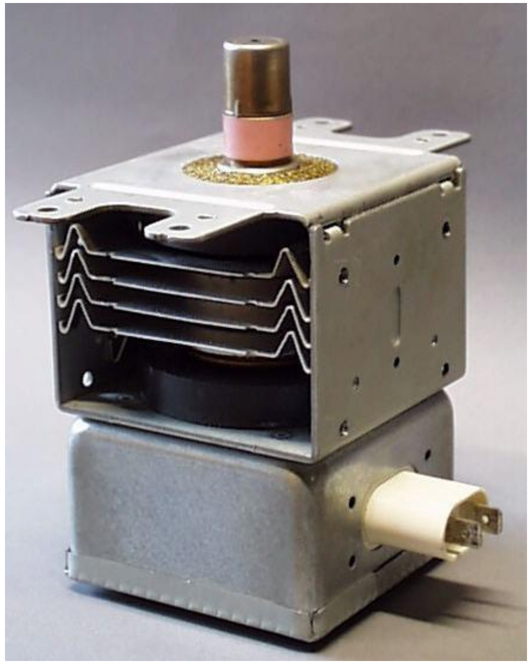
The historian of the Office of Scientific R&D, **James Phinney Baxter III**, wrote:
"*When the members of the Tizard Mission brought the cavity magnetron to America in 1940, they carried the most valuable cargo ever brought to our shores*."

However Sir Edward Appleton wrote: *"Those who were in the business know how much the practical development of the cavity magnetron - the development that made it something that could go into operational use - was due to* ***Megaw****."*

June 2024 Birmingham plaque

Courtesy University of Birmingham

Cavity Magnetron Today



These £60 cavity magnetrons power the microwave ovens, as installed in 93% of UK households.

In USA, cavity magnetrons are installed in over 10 million new microwave ovens each year.

Image Wikipedia

Historical References

‘Origins and Evolution of the Cavity Magnetron’,
International Conference Proceedings, Bournemouth, April 2010
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Yves Blanchard, Gaspare Galati, and Piet van Genderen
Thales (France), Tor Vergata University (Rome), Delft University of Technology (The Netherlands)
IEEE Antennas and Propagation Magazine, Vol. 55, No. 5, October 2013

“Tuxedo Park”
Jennet Conant, ISBN: 978-0-684-87288-9
Simon and Schuster, 2002.

“Blind Bombing: How Microwave Radar Brought the Allies to D-Day and Victory in World War II”
Norman Fine, ISBN: 978-1640122208
Potomac Books, 2019.

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Alex Magoun and Yves Blanchard

SCANNING OUR PAST

The Cavity Magnetron Developments Which Enabled the Rapid Deployment of Airborne Radar Systems in World War II

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In February 1935, the Daventry radar experiment, led by Robert Watson-Watt, detected the presence of an aircraft by using reflected radio waves [1]. Later that year, the Chain Home radar system design started [1], with the first installation in 1938 covering the approaches to the Thames Estuary. This enabled the detection of incoming aircraft at 160-km range and directed interception fighters to within 6.5 km of the target. This system used 100-kW–1-MW high-energy pulses generated at 20–50 MHz and was later extended to cover the U.K. east and south coasts as well as parts of the west coast. Compared to today's microwave radar systems, this was a basic design with wooden and steel towers supporting the physically large high-frequency (HF) antennas.

Air-to-surface vessel (ASV) and AI radars [2], which started entering service in 1939, used slightly higher very HFs (VHFs) around 200 MHz (a wavelength of 1.5 m) and typically employed dipole and Yagi fixed antennas. Fig. 1 shows the forward-looking, long-range ASV antennas of ASV Mk. II on a Lockheed Hudson maritime patrol aircraft, used by the Royal Air Force (RAF) Coastal Command. It was realized that operating at higher frequencies would allow the use of smaller antennas and would be very desirable for airborne operation. However, at that time, it was not possible to generate sufficient transmitter power, especially at centimetric wavelengths. Achieving this goal was a topic of extensive prewar research.

Boot and Randall [3] at the University of Birmingham, Birmingham, U.K., were invited by the team developing radio

Digital Object Identifier 10.1109/JPROC.2025.3627402

10.1109/JPROC.2025.3627402

Proceedings of the IEEE

July 2025