The Cavity Magnetron designs which enabled WW 2 microwave radar

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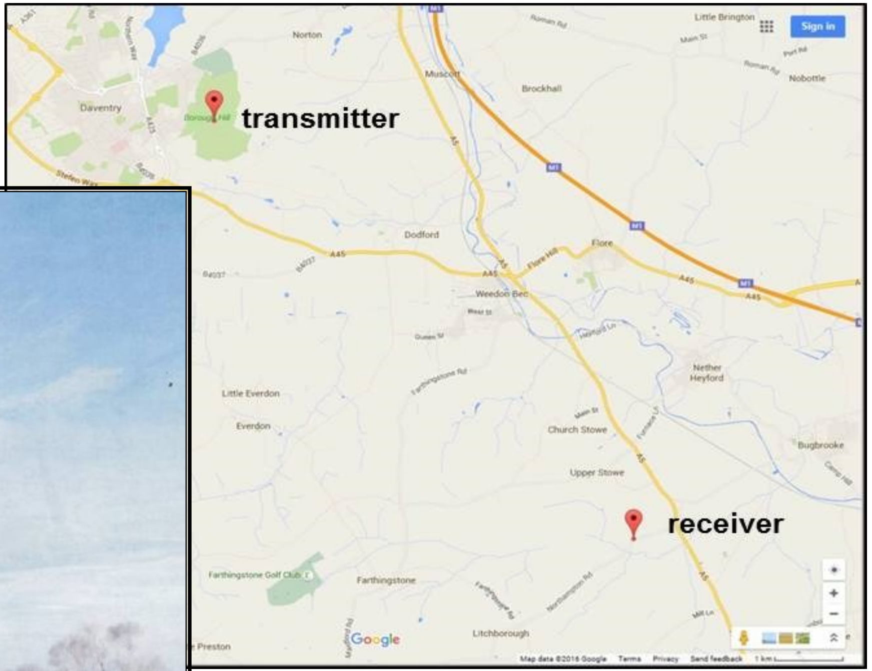
Why am I talking about the Magnetron?

IEEE President, Tom Coughlin, congratulating myself in June 2024.

Overview

- Early British radar and microwaves
- Cavity Magnetron development before 1939
- The Birmingham initial technical advances
- Subsequent GEC engineering enhancements
- The Tizard Mission to the US
- Improving the frequency stability of the device
- Wartime airborne radar systems
- Other International magnetron developments
- Recognition for the inventors

The Daventry Experiment: 26 February 1935

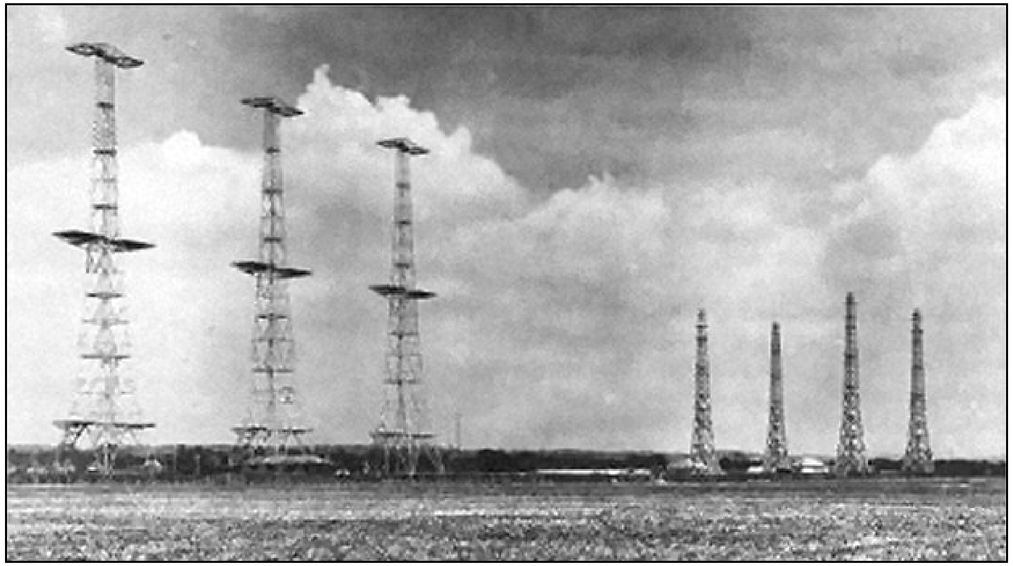


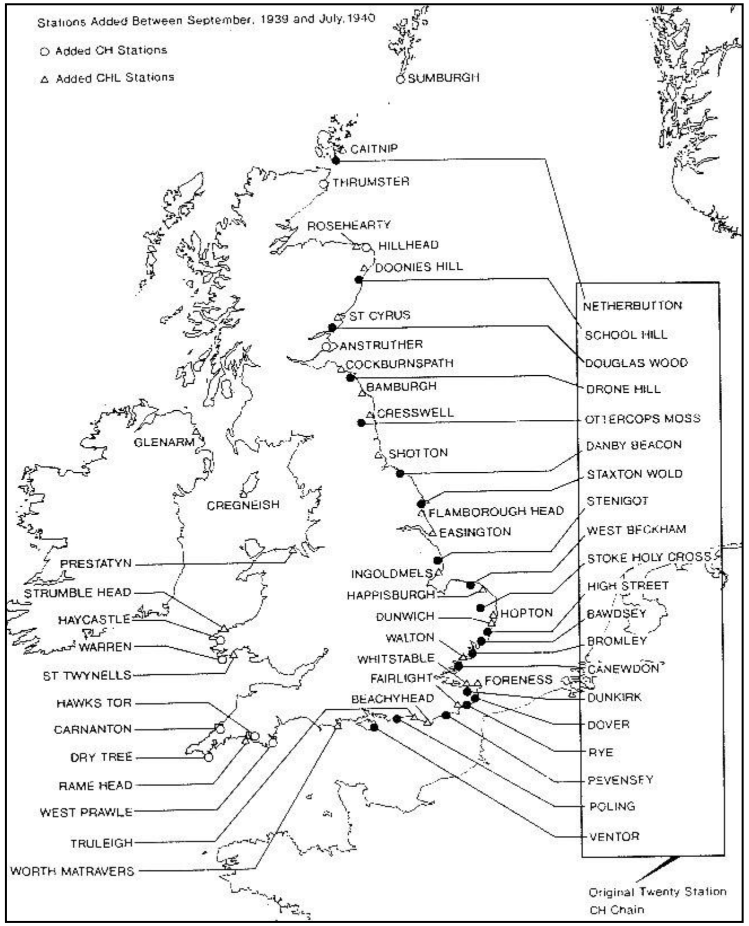
Painting by Roy Huxley

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

Courtesy Hugh Griffiths

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 WW2 he became Scientific Advisor on Telecommunications to the Ministry for Aircraft Production, travelling to the US in to advise them on the severe 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 2 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**.

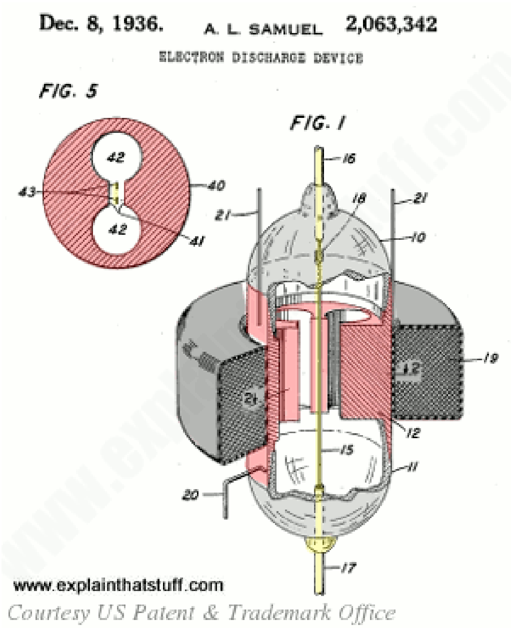
Mk II ASV antennae

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**



The magnetron name originated from work by Albert Hull in 1921 at GE Schenectady in New York on the use of magnetic fields to control the current in a vacuum tube.

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.

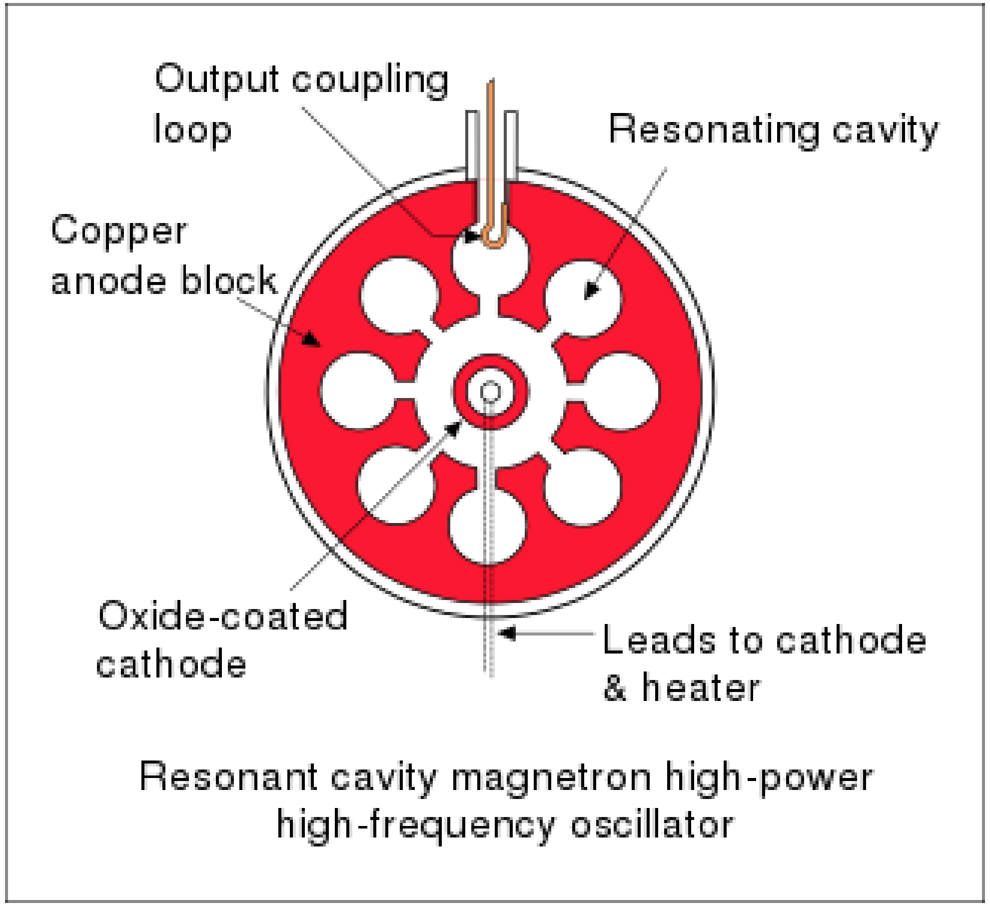
Nowhere in the world **in 1939** was there a **working, pulsed, *cavity magnetron*** capable of **generating 10 kW or more peak power at wavelengths of 10 cm or less**, which had a **compact portable size**, used a **small permanent magnet** and which was readily capable of being **manufactured at scale**.

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

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 cavity resonators

The Birmingham technical advances

Randall and Boot showed their first copper resonator block to Lawrence Bragg and Edward Appleton (*UoE Principal 1949-65*) 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 3GHz, 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 exactly the appropriate time for 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 to maintain the vacuum and it required an external electromagnet to create the required large magnetic field.

Courtesy London Science Museum

Birmingham Electromagnet

Courtesy University of Birmingham

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 magnetron design.

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

Photo after IEEE AP Magazine 2013

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 with 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.**

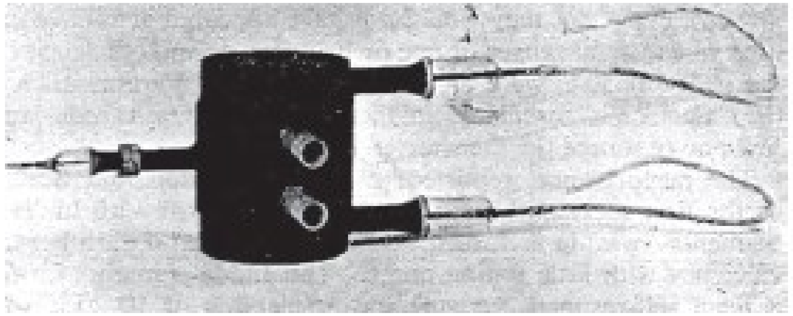
Finally they combined the Birmingham multi-resonator system with a large oxide coated cathode to construct a device with a **permanent** magnet, to improve lifetime and enable manufacture in quantity.

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

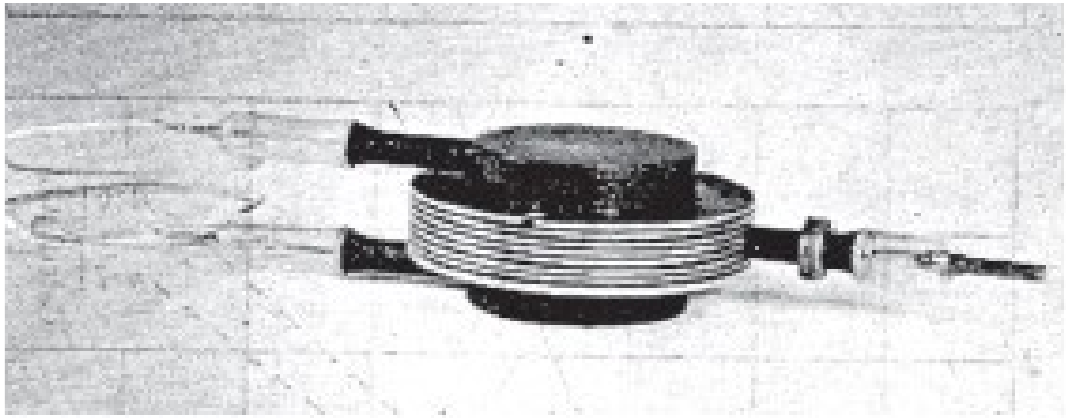
Maurice Ponte

M16 8 segment Anode

1940 GEC initial Magnetron designs



The first prototype, E-1188, which used a Birmingham resonator, was a water cooled design with an associated 50 lb weight magnet.
On 16 May 1940 it gave a 500 W output.



E-1189-1 was on 29 June 1940 a 6 cavity re-design for an airborne radar trial, later extended to 8 cavities.

It combined a compact sealed-off all-metal air-cooled housing, a reduced axial dimension to achieve a 1.5” air gap for a 6 lb magnet, with an enlarged thoriated-tungsten oxide coated spiral cathode, gave initially a 3 kW output.

Images from IEEE AP Magazine 2013

GEC E-1189 Magnetron

E-1189-2 or b with an oxide coated cathode increased power to 15 kW with improved lifespan. By 1941 power 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.

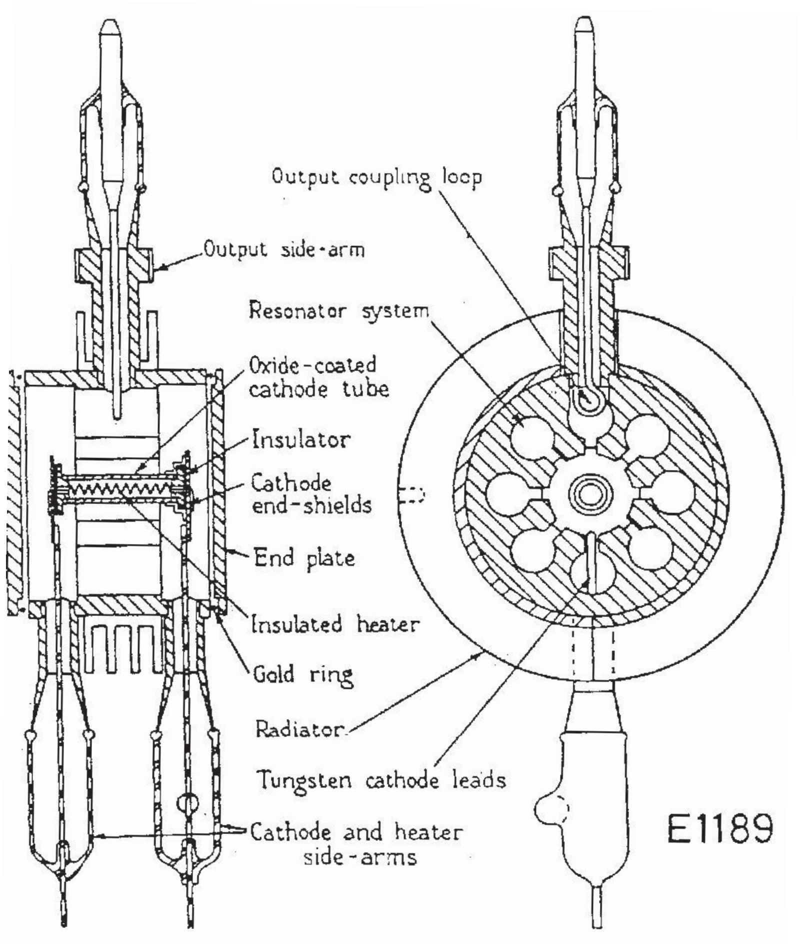
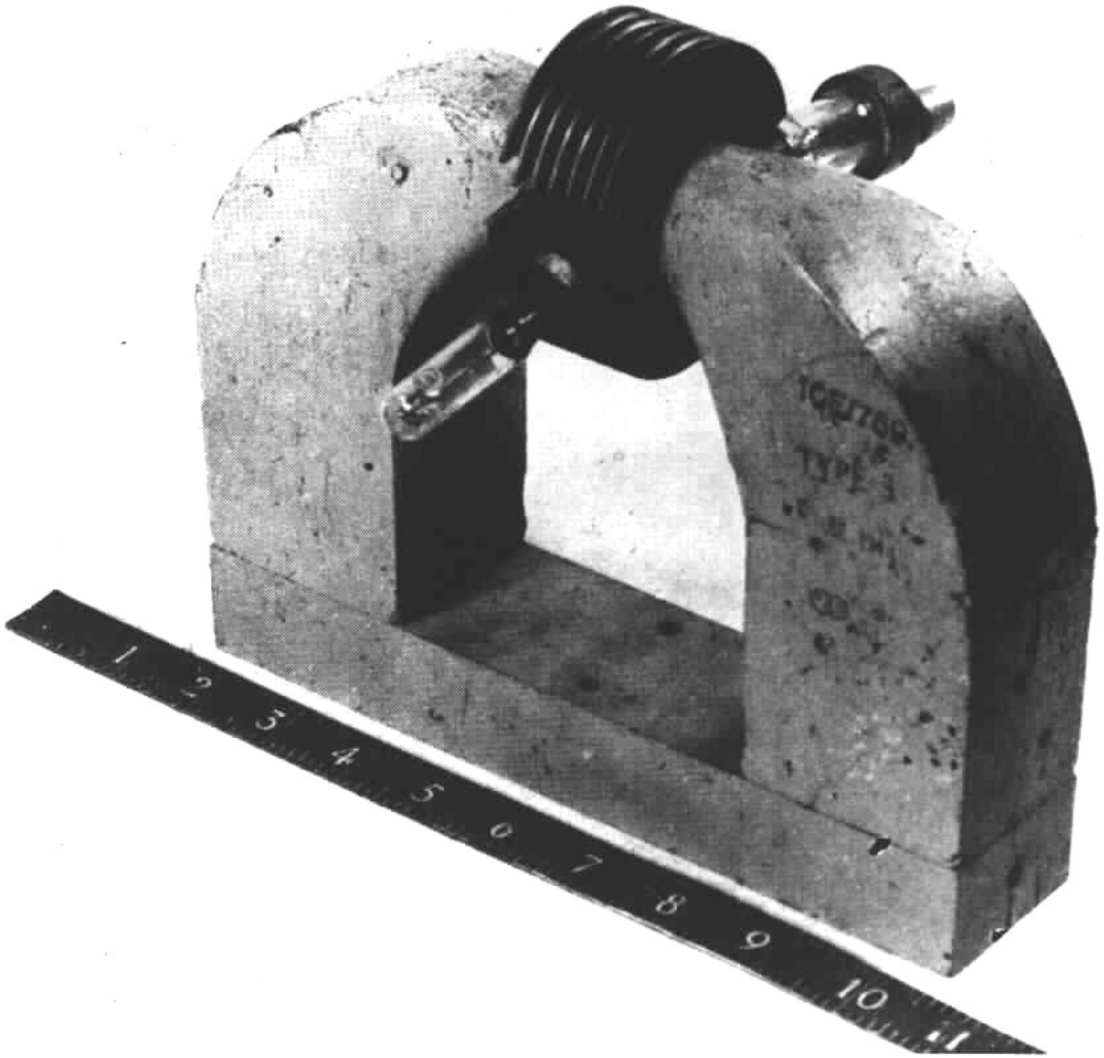


Image Radio Museum Lucerne, Switzerland & IEEE AP Magazine 2013

GEC E-1189 reduced axial dimension Magnetron with permanent magnet



Navy used first cavity magnetron radar

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. On the 36 foot high mast, the radar system was able to track a surfaced submarine at 4,000 yards range.

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

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 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.

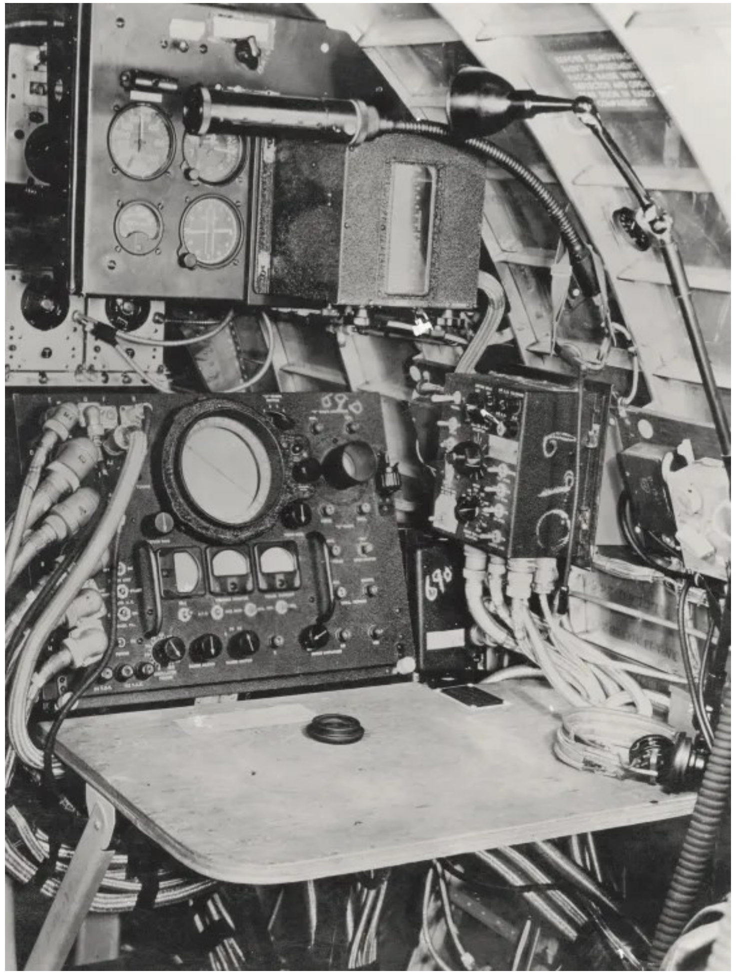
Image MIT Museum

MIT radar development

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

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

First flight trial on March 7 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 worked on klystrons at Birmingham, where he had designed a centimetric wave klystron with 10 kV voltage.

He brought this later knowledge in July 1941 to *improve the frequency stability* of the cavity magnetron design.

He developed **"strapping"** of the cavities to alleviate mode hopping and generate only a single output frequency.

His strapped magnetron became the CV64 device.

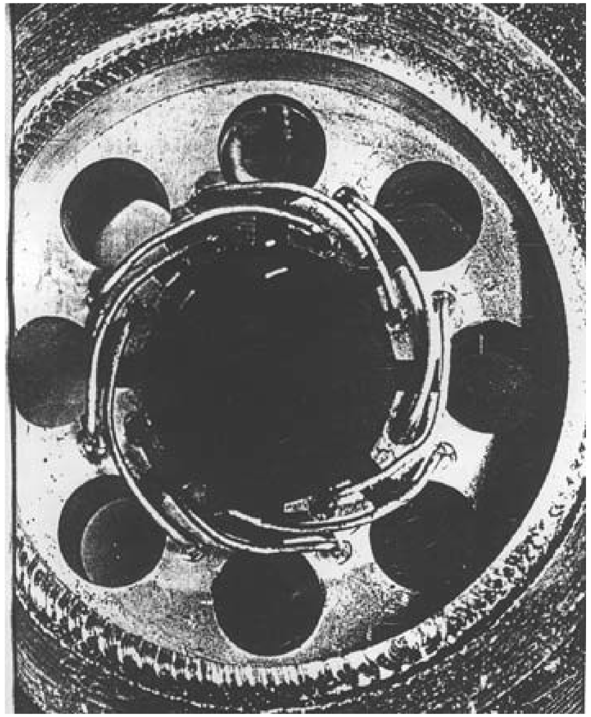


Figure from TRE report T 1858

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 used the CV64 magnetron.

Radar scanner with a waveguide feed and reflector

Image Wikipedia

Magnetron based centimetric airborne radar

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

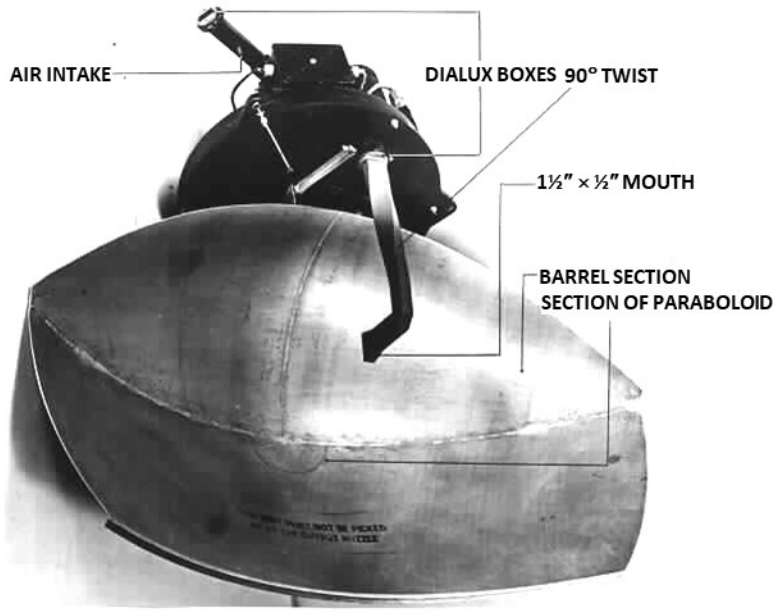
The most widely-deployed British magnetron radar was the H2S ground mapping bombing aid. H2S Mk. I, ~ 3 GHz, entered service in 1943.

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

By 1945, some 250,000 magnetrons had been delivered for British deployment!

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

(Ewart Farvis, the first UoE Prof of EE, worked at Malvern during WW 2 not on radar, on countering the beams used to direct enemy bombers over the UK.)



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

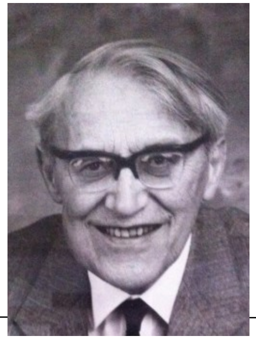


Image Malvern Radar and Technology History Society

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 Rad Lab hand built radars
were installed at the Boston Airport.

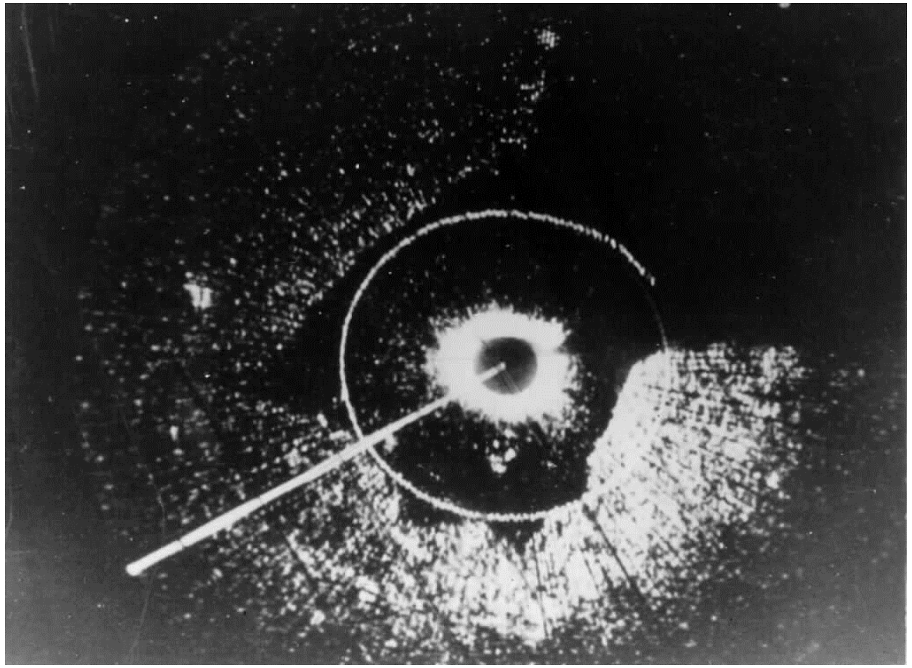
12 US pilots flew the B-17s to England, in late 1943.

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.

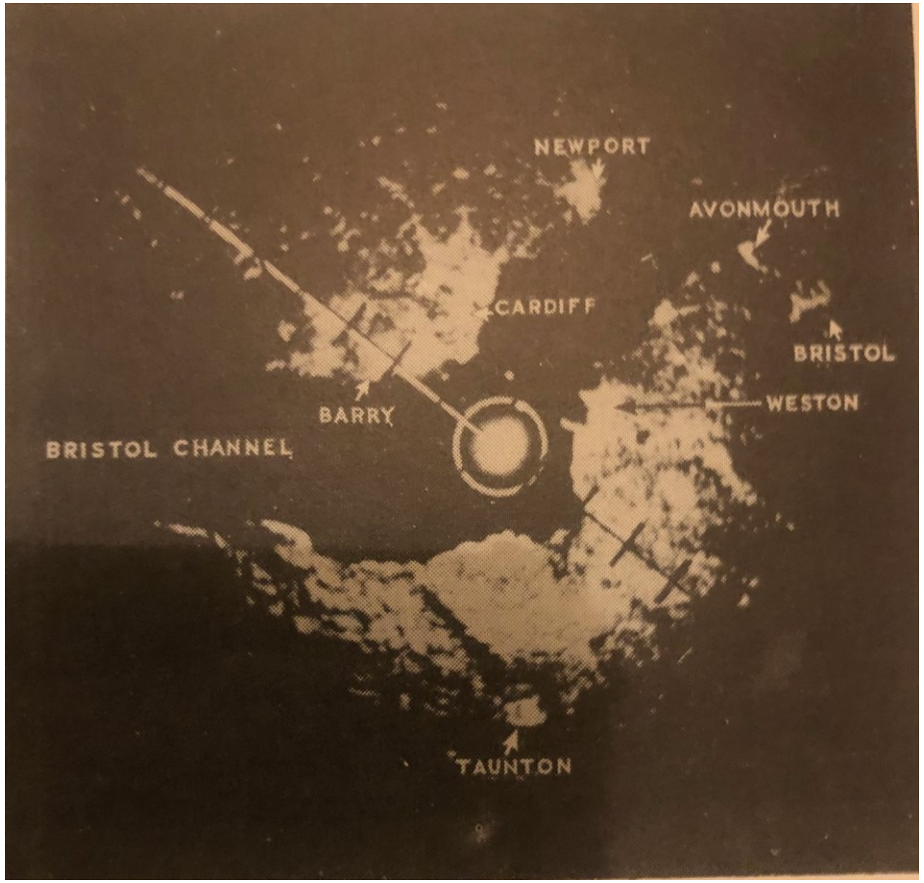
Norman Fine from MIT Technology Review, Oct 2024

Magnetron 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!

Inter-services Radar Manual, 1950, War Office No. 1543

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 WW2.

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

Russian Developments

Alekseev and Malairov's Russian cavity magnetron was well known at Telefunken during WW 2!

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!

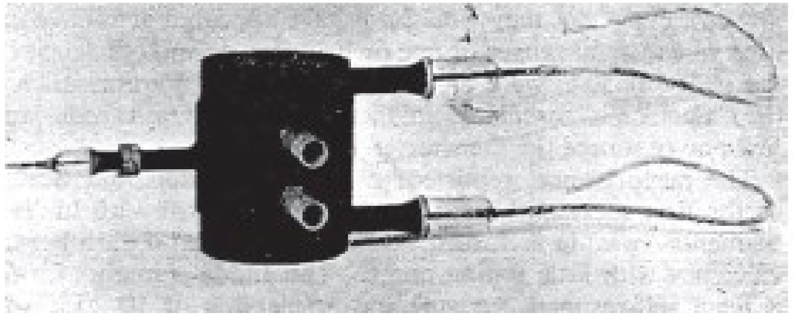
Japanese Developments!

In April 1939 Nakajima in Japan had designed an eight-cavity "M3" magnetron which generated 500 W output at 10 cm, in advance of the Birmingham device design!

He also developed "Rising sun" resonator designs.

In April 1953, Nakajima discovered the E-1188 GEC device on his visit to the London Science Museum.

On examination he noted: "the dimensions of the glass covering the vacuum; the anode water-cooling system; and the anode mechanism; were all very similar to his own "M3" cavity design".



E-1188 GEC Magnetron

doi 10.1098/rsnr.2004.0058

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

Progressive Technical Developments

Randall and Boot developed the CW magnetron combining their cylindrical resonator design with a vacuum system located inside the anode structure and an induction coupling loop inside the cavity.

The **Birmingham laboratory device** provided: increased power level; with outstanding improvement in efficiency.

Megaw at GEC, **further engineered** a higher powered **pulsed** magnetron with a sealed-off air-cooled housing, minimised air-gap, and an oxide coated spiral cathode.

Sayers later developed strapping to improve the frequency stability.

These technical developments enabled large scale manufacture for the deployment of airborne radar which was essential to winning the Battle of the Atlantic.

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 2.

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 to enable 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*."

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****."*

Conundrum

GB Patent 588,185, 22 Aug 1940, by RANDALL, BOOT and WRIGHT.

"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."

Figures and Tables in this Patent include the details for the later magnetron GEC designs developed but Eric Megaw is not named as an inventor!!

Sir John Turton Randall

Employed by GEC Wembley, 1926-37, before moving to Birmingham University.

In 1943 he was awarded (with Boot) the Thomas Gray prize, Royal Society of Arts,
the 1945 Duddell Medal and Prize by the Physical Society, London,
the 1958 John Price Wetherill Medal (with Boot and Sayers) of the Franklin Institute,
the 1959 John Scott Medal (with Boot) of the city of Philadelphia.

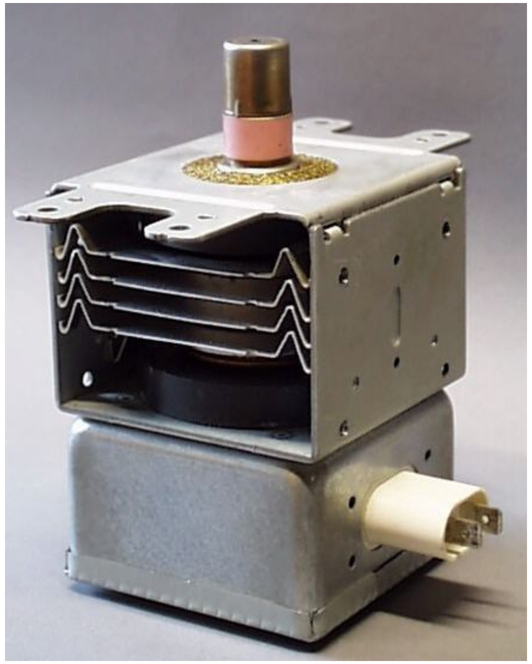
Randall was appointed, in 1946, Head of Physics at King's College, London, where he formed and directed what is today the "Randall centre for Cell and Molecular Biophysics", overseeing the experimental work which led to Watson and Crick's discovery of the structure of DNA.

In 1970 he moved to research on biophysical methods at the University of Edinburgh.

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

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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

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Jennet Conant, ISBN: 978-0-684-87288-9
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Norman Fine, ISBN: 978-1640122208
Potomac Books, 2019.

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