MAGNETRON DEVELOPMENTS AT E2V

Dipendra J. Mistry, Mauro Mineo
e2v Technologies, 106 Waterhouse Lane, Chelmsford, Essex, CM1 2QU, UK

***Abstract** – Magnetrons were first developed to meet the demand for a high power, high frequency RF source in radar systems during WWII. Since this time, a significant amount of design innovation has taken place to improve device performance for a number of different applications.*

This paper will trace some of the key aspects of magnetron design, operating principles and technological developments which have led to their rapid adoption in medical and marine radar applications. The latest devices are the product of historic developments which have been realised through e2v's heritage in vacuum electron tube devices.

INTRODUCTION

Magnetrons emerged as efficient, high power RF sources during WWII in high power radar systems. Since then they have been designed to suit a number of different applications, as summarised in Fig. 1. Magnetrons for civil marine applications have been manufactured on the e2v Chelmsford site since 1947 [1]. The earliest production devices were based on S-band wartime designs, and were soon accompanied by X-band (8-12 GHz) devices.

In the 1950's the magnetron was adopted for use in X-ray External Beam Radiotherapy (EBRT) [2], now a well-established technique for the treatment of cancerous tumours. These systems require a pulsed RF source to accelerate electrons in the cavities of a linear accelerator (linac). The accelerated electron bunch is then directed toward a dense target material, to generate high-energy X-rays for treatment.

The magnetron is a natural solution for EBRT at lower X-ray energies due to its compactness and efficiency, compared to klystron devices. Klystrons typically operate at voltages twice that of a magnetron, thereby requiring immersion in oil to prevent electrical breakdown. A higher power output is realisable for a given operating frequency; however there is inevitably a trade-off in size and weight, which make these devices more difficult to mount onto a rotating gantry system.

In addition to commercial radar and medical linac applications, magnetrons have more recently found their application in driving linacs for cargo and vehicle inspection. In this case, high energy X-rays are used to image the contents of shipping containers and vehicles [3].

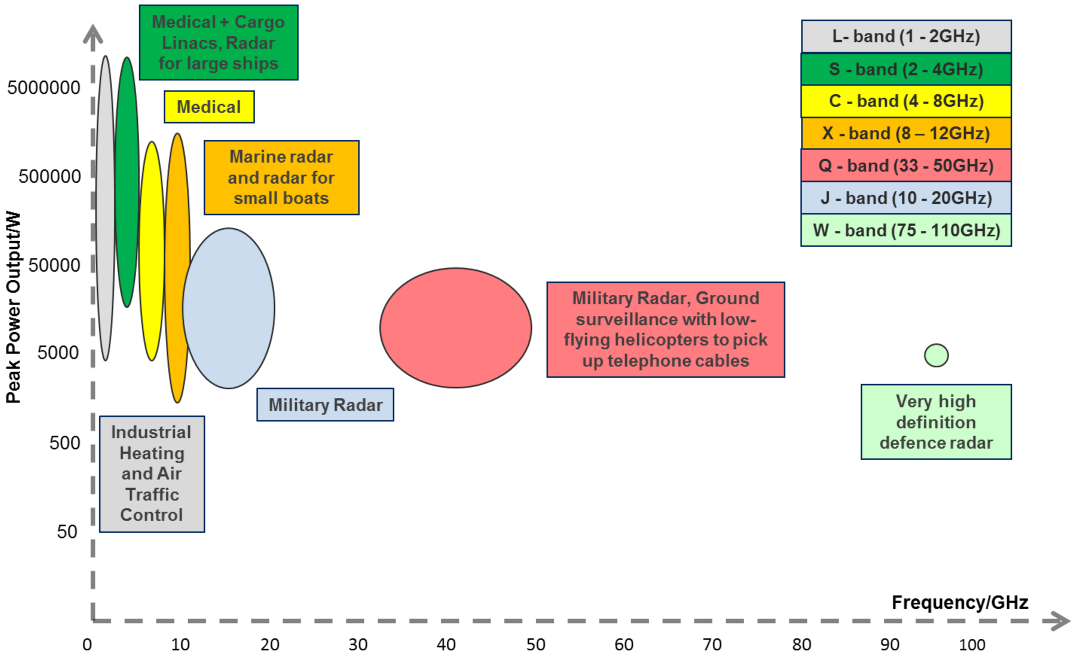

Figure 1. A plot of Power versus Frequency to compare e2v's historic magnetron range.

OPERATING PRINCIPLES

The magnetron is a crossed-field, vacuum electron device capable of generating microwave power up to Mega-Watt levels (in pulsed operation).

The core elements of a magnetron are the electron source (the cathode) and the resonant structure (the anode), as depicted in Figure 2. A high-voltage between anode and cathode and a magnetic field parallel to the magnetron axis are applied, in order to achieve a crossed-field configuration over the region between the anode and cathode (interaction region). RF power is generated by interaction between the resonant structure and the electron–cloud, which is rotating around the cathode as a result of the initially applied static fields (Lorentz force).

Electrons are emitted from the cathode surface usually by thermionic emission. A thermionic cathode generally consists of a resistive filament, which is in thermal contact with a layer of emitting material on the cathode surface. Electrons are emitted when their energy is sufficient to overcome the work-function of the emitting surface. The emission properties of the cathode are therefore driven by the temperature and the material properties of the emitting surface.

The anode consists of an even number of microwave cavities realised in a metallic block. In principle, interaction between the electron-cloud and anode can occur through any of the infinite number of resonant-modes supported by the system of resonators. However, we focus our attention to one in particular, which is called π-mode: this mode represents an RF field which is 180° (or π) out of phase between adjacent cavities (Figure 2). For reasons which will be explained in the next paragraph, the interaction between the electron cloud and the π-mode is the most effective in a magnetron.

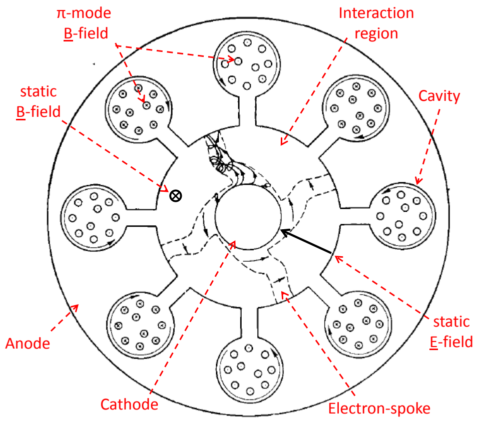

Figure 2. Space-charge in oscillating magnetron [4].

The interaction between the electron-cloud and the anode can be qualitatively described as follows: the electron-cloud is emitted from the cathode and rotates in the interaction region due to the applied static fields. The electromagnetic noise carried by the electron-cloud induces an EM field at the cavity apertures, thus exciting resonant modes of the anode. Depending on the angular velocity of the electrons, one particular resonant mode is excited. The RF field at the cavity apertures starts decelerating or accelerating the electrons, depending on the relative phase; the electrons loose kinetic energy (on average) and the resonant-mode progressively gains strength. The electron cloud is then deformed more and more under the effect of the RF field creating electron-spokes. In this situation the electrons reach the anode surface and the interaction process saturates, i.e. the magnetron is in regime operation.

The energy transferred to the resonant structure depends on several parameters, but in particular on the number of RF phase shifts which the electron-cloud experiences in 360° (synchronism conditions). Presenting 180° phase shift at each cavity aperture, the π-mode is the most effective among the possible resonant-modes. The operating frequency of the magnetron is therefore determined by the π-mode frequency.

MAGNETRON DESIGN

The design of a magnetron involves a great deal of complexity compared with a linear beam device, such as the klystron. Challenges in the design of a crossed-field device arise because different design parameters affect the whole magnetron system, rather than a particular section. In contrast, many aspects of a linear beam device can be designed in isolation, and then assembled to verify operational performance.

The main parameters which drive most of the magnetron design choices are the operating frequency and the output power requirements. Its constituent parts are the anode, the cathode, a sidearm and an output structure, as depicted in Fig. 3. In addition, an external magnetic circuit is required to generate the static fields required for the correct operation.

The operating frequency drives the geometrical dimensions of the anode cavities, and more generally the dimensions of the whole device. On the other hand, the anode dimensions must be balanced with the output power requirements. In fact, the power that must be dissipated on the anode block, and the RF power density generated in the device are proportional to the output power. Thermal management and RF power-handling must be properly considered to avoid device failure or RF breakdown.

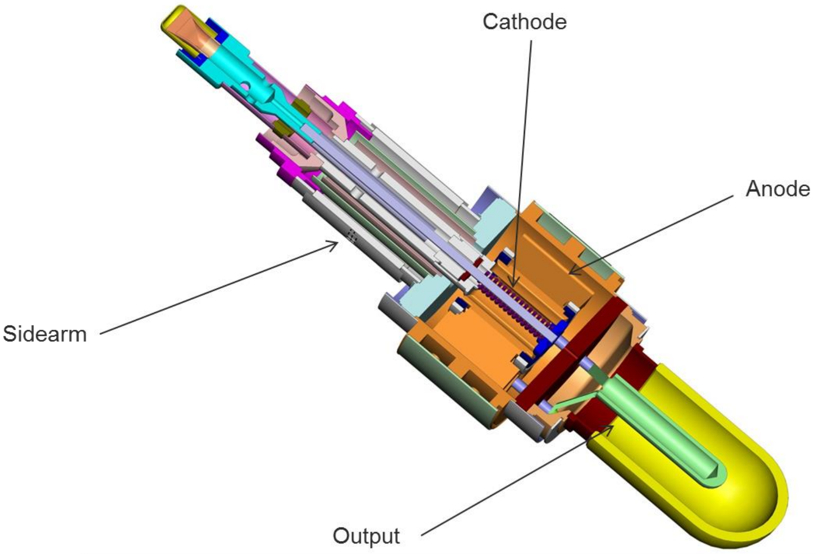

Figure 3. Cross-sectional view of the BM100L industrial magnetron manufactured by e2v.

As already introduced, the anode design sets the magnetron frequency of operation. Its geometry is however carefully chosen to balance a number of key parameters, such as power handling, efficiency and frequency stability. It is not unusual that the separation between the π-mode frequency and the other resonant modes is too small to assure efficient stability of the magnetron during operation. Mode separation can be improved by adopting suitable techniques. The most common is called *strapping* and consists of electrically connecting alternate vanes together by means of concentric metal rings.

The design of the cathode is strictly related to the anode, and vice versa: geometrical dimensions and material properties of the emitting surface are carefully chosen to balance the whole interaction process. Suitable sidearm designs are chosen to support the cathode and heater filament structures within the anode, providing, at the same time, an external interface with a DC electrical input.

To ensure efficient and stable magnetron operation it is crucial to have a uniform magnetic field over the interaction region. This magnetic field can be produced by an electromagnet or a permanent magnet, both of which require careful design to achieve the desired level of performance.

The output structure consists of a RF transition to couple-out the generated power from the anode, and of an output window to isolate the inside of the vacuum envelope from the external environment. The output window is usually made of a special glass, which is joined to the main copper body of the magnetron using a NiCoFe alloy (having the same thermal expansion rate as glass).

In terms of device manufacture, the anode, output and cathode structures are brazed under a protective atmosphere. Prior to RF testing, devices are fitted to a vacuum pump for bake-out and cathode activation.

In summary, the reliable operation of a magnetron requires demanding conditions such as ultra-high vacuum ($< 10^{-7}$ Torr), high-voltage (kV), thermionic emission (hundreds of °C at cathode surface) and high power densities that need to be dissipated on the anode structure. The mechanical design, material choice and processing techniques involved in its manufacture play a crucial role in achieving the desired operational specification. A number of geometrical and electrical parameters come into play during the interaction process - making its optimization very challenging during the design phase.

TECHNOLOGICAL DEVELOPMENTS

There are two key areas for medical and commercial radar magnetrons, which have seen significant development over the past few decades, namely product reliability and power output.

Reliability

The design of the magnetron has adapted over the years to meet the new requirements imposed by different applications. In the case of EBRT, these requirements aim to improve future platforms to increase patient throughput, whilst maintaining treatment quality and efficacy. Similarly, in commercial radar these requirements seek to improve service life and performance.

Life

By their nature all magnetrons will arc internally on an occasional basis, and magnetron end of life is usually characterized by the onset of high arc rates. This had lead e2v to develop magnetron designs that reduce arc rates by an order of magnitude, thereby improving product reliability, and the useful life-time of the magnetron in fielded systems [3]. In the case of radiotherapy applications, the effects of arcing are monitored and managed using system software to ensure that the correct dose is delivered.

Magnetron life is determined by cathode exhaustion, following the progressive depletion of electron emissive material on the cathode surface during high voltage operation. The rate at which the emissive material is removed depends on the applied pulse width, operating duty cycle and magnetron peak current [1]. As such, the cathode plays a crucial role in improving product reliability and in-service life for any application.

In the case of medical magnetrons, reliability improvements have been realised through the development of a novel cathode design [5]. This technology is less susceptible to arcing due to the material choice and design, and therefore experiences a lower depletion rate of emissive material compared to its predecessors.

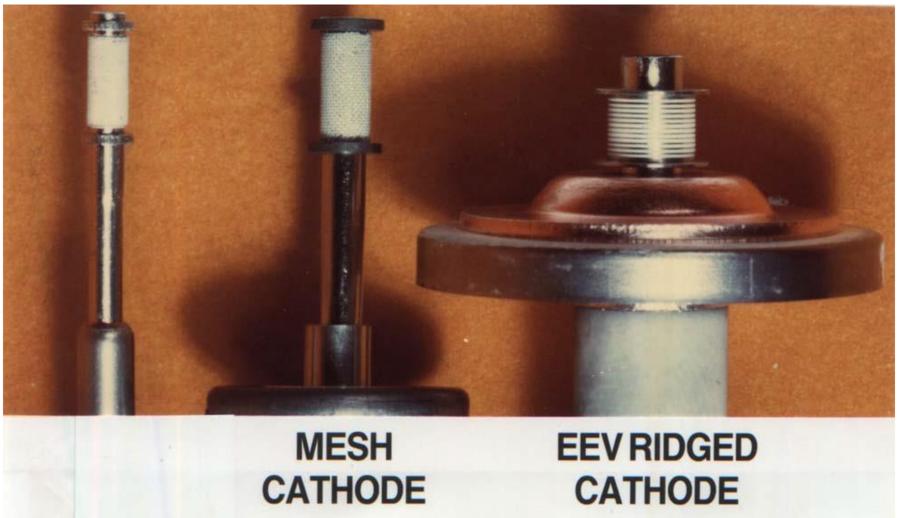

Figure 4: Oxide cathode assemblies on Generations 1-3 of marine magnetrons manufactured by e2v.

In the 1970's, EEV developed a novel cathode design for commercial radar magnetrons to improve the life of oxide cathodes [6], as shown in Fig. 4. This was driven by the introduction of solid-state modulators which imposed new requirements on magnetron stability and life. In the 1980's, EEV introduced a new range of X-band marine magnetrons which incorporated a patented long-life ridge cathode [1].

Mechanical Stability

The majority of EBRT machines utilise a rotating gantry system to direct X-ray beams to the tumour site from different directions. A key figure of merit for this application is the change in X-ray dose rate upon gantry rotation, which can lead to incorrect doses being delivered during a treatment. This requires the components located on the gantry to be stable under rotation. Due to the compact nature of the magnetron, compared to the klystron, system designers are able to locate this device directly on the rotating gantry.

Over the years, a number of improvements have been made to the mechanical design of the medical magnetron to improve structural stability under rotation. Design changes made at e2v have met this requirement by managing mechanical resonances within the magnetron structure through computer modelling. This has led to the introduction of stiffer cathode support structures to prevent cathode movement under rotation. It is worth noting that even small changes in cathode position can cause measurable changes in power output and X-ray dose.

Similarly, during the early development of marine magnetrons in the late 1960's, a material change was made in the sidearm, from glass to ceramic insulation. This resolved the issue of cathode movement under low frequency vibrations, resulting in devices which could withstand more stringent environmental specifications [1].

Mode Suppression

The current state-of-the-art in civil marine magnetrons is the “Gen 4” device, which has been installed in radar systems, since 2002, see Fig. 5. A design optimisation was made to suppress RF emissions in undesired modes, even as the magnetron approached end-of-life [1].

This goal was achieved without increasing the size of the magnetron, by adding a completely novel frequency selective attenuator [7]. The tuned circuit comprised of a dielectric resonator split into two regions by a conducting ring. Dimensions were chosen so that any asymmetric current flowing around the anode, due to undesired modes, will couple magnetically to the lossy attenuator in a high order mode [1].

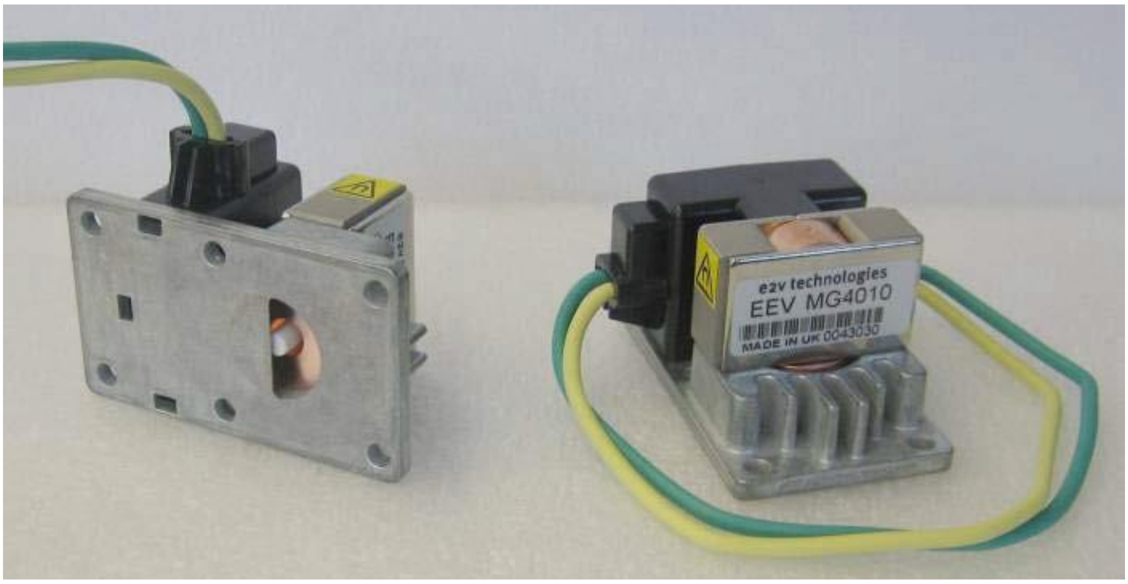

Figure 5: The Gen 4 12.5 kW marine radar magnetron manufactured by e2v.

Power Output

In medical applications, an increase in peak power output offers the system designer the opportunity to use higher energy X-rays, which can be used to treat deep seated tumours. Higher peak power levels can also permit a higher dose and therefore patient throughput, or offer the linear accelerator designer the option to use fewer accelerating cavities for a given output energy; thus, reducing the size of the system. Magnetron power design parameters are constantly being optimized to fulfil the above requirement, while maintaining product reliability.

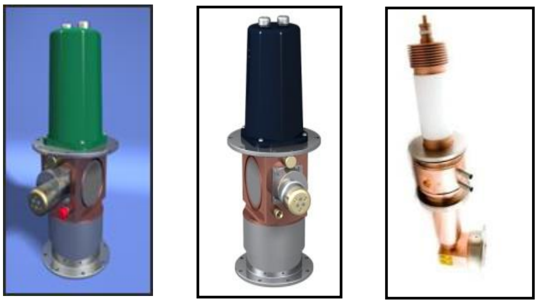

Figure 6: Displays a range of S-band medical magnetrons manufactured by e2v. These include the MG5193 (left), the MG7095 (middle) and future high power S-band magnetron (right).

An example of this is the MG7095 magnetron, which offers ~20% increase in peak and average power, whilst maintaining the same in-service life as its predecessor, the MG5193 magnetron, see Fig. 6. This power output was realised through a number of design changes which included:

- A re-design of the cathode and sidearm assemblies to improve reliability when operating at higher voltage and power levels.

- Improved vacuum processing techniques which sought to reduce the number of impurities within the vacuum envelope.

e2v are currently developing a high-power S-band magnetron with over double the power capability of existing medical magnetrons, while retaining low arc rates for improved reliability and life in EBRT machines [3]. In this case, the power output requirements are leading to a series of design improvements which can be summarized as follows:

- A new design of the whole anode structure to improve the overall anode thermal management;
- A consequent re-design of the cathode and sidearm assemblies;
- A re-design of the strapping technique to improve mode-separation;
- A re-design of the output coupler section to enhance power-handling capabilities and suppression of undesired resonant modes, simultaneously.

Standard S-band medical magnetrons are capable of delivering a peak power of 2–3MW, while the new magnetrons under development at e2v have a target of 7.5MW peak power, offering the power capability of a klystron at half the voltage and in a compact space, resulting in savings in both system size and cost.

CONCLUSION

e2v continues to develop magnetrons with an improved performance to support the medical and industrial markets. Developments in magnetron technology continue to require innovations in material science, device physics and manufacturing techniques. As a result, the magnetron remains the prime source of RF power for medical and commercial radar applications.

REFERENCES

1. M. Brady and M. Edwards, "Developments in Marine Radar Magnetrons", in Proc. IEEE Int. Conf. Origins Evolution Cavity Magnetron, pp. 58-63, Apr. 2010.

2. D.I Thwaites and J.B. Tuohy, "Back to the future: the history and development of the clinical linear accelerator", Phys. Med. Biol. 51 (2006) R343–R362, pp 351-352, June 2006.

3. D.J. Mistry, T.A. Cross and C.R. Weatherup, "RF Sub-Systems for Cargo and Vehicle Inspection", IPAC Proc. vol. 4, International Particle Accelerator Conference, Dresden, Germany, pp 1917–1922, June 2014.

4. G. B. Collins, *Microwave Magnetrons*, McGraw Hill, New York, 1948.

5. Magnetrons Cathodes, C. Reynolds and R.C. Lodge, e2v Technologies (UK) Limited Patent, US9177749

6. Magnetrons AH Pickering English Electric Valve Co Patent US4380717
7. Strapped Magnetron with a dielectric resonator for absorbing radiation, M. Brady, e2v technologies UK Ltd, Patent US 7199525