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Experimental Study of Cyclotron-Related Electromagnetic Waves and Their Interaction with Electronic Circuits

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ABSTRACT: Electromagnetic fields generated by systems involving charged-particle motion are important in accelerator physics, microwave engineering, and electromagnetic compatibility (EMC). A cyclotron accelerates charged particles by the coordinated action of a magnetic field and a radio-frequency (RF) electric field, while accelerated charges and time-varying fields provide a general physical basis for electromagnetic radiation (Lawrence & Livingston, 1932; Wiedemann, 2015). The present study investigates, experimentally, how microwave electromagnetic fields interact with electronic circuits and uses a magnetron-based laboratory source as an accessible experimental model for phenomena related to charged-particle electromagnetics. The apparatus consisted of a high-voltage power-supply/transformer unit, high-voltage capacitor, microwave magnetron, electrical connecting leads, and a metallic enclosure lined internally with aluminium. The electromagnetic response of a mobile phone, digital camera, calculator, radio, and lamp was observed. At an initial source-to-device separation of approximately 30 cm, temporary functional disturbances were observed, and the disturbances generally became more pronounced when the devices were moved closer to the source. Inside the aluminium-lined enclosure, the response was spatially non-uniform: some positions produced stronger disturbances than others. This behaviour is physically consistent with reflection from the conducting enclosure and interference between incident and reflected microwave fields, producing spatial maxima and minima. The mobile phone showed screen instability and temporary touch-response disturbance at some positions, while the radio, calculator, digital camera, and lamp also exhibited abnormal responses. The study interprets these observations through electromagnetic coupling, induced voltage/current, frequency-dependent susceptibility, and spatial field redistribution. Because calibrated measurements of field strength, power density, and exact operating frequency were not performed, the results are reported as qualitative evidence of electromagnetic susceptibility rather than as calibrated failure thresholds. The work provides an experimentally accessible bridge between accelerator-physics concepts, microwave generation, and EMC and offers a basis for future quantitative measurements.

KEYWORDS: Cyclotron, Electromagnetic Waves, Microwave, Electromagnetic Interference (EMI), Electronic Circuits, Electromagnetic Susceptibility.

1. INTRODUCTION

Cyclotrons are circular particle accelerators in which charged particles gain energy through repeated interaction with an alternating electric field while a magnetic field bends their trajectories. The original cyclotron concept established a practical method for accelerating light ions without requiring a single extremely large accelerating voltage (Lawrence & Livingston, 1932). Modern accelerator physics extends these principles to a wide range of circular accelerators and RF systems, where beam dynamics, resonant fields, and electromagnetic interactions are central to system operation (Lee, 2018; Wiedemann, 2015).

The physical foundation of the present study is the Lorentz force, $F = q(E + v \times B)$, which determines how a charged particle responds to electric and magnetic fields (Griffiths, 2017). In an ideal non-relativistic cyclotron, the characteristic angular frequency is $\omega c = |q|B/m$ and the corresponding frequency is $fc = |q|B/(2\pi m)$. This frequency depends on particle charge, mass, and magnetic-field strength and is distinct from the microwave operating frequency of a particular laboratory source. This distinction is important: a cyclotron does not, in general, operate as a simple 2.45-GHz microwave generator. Rather, cyclotron physics provides the charged-particle and RF-field framework relevant to the present electromagnetic analysis (Wiedemann, 2015).

Accelerated charges radiate electromagnetic fields, and time-varying electric and magnetic fields can propagate energy through space. Maxwell's equations provide the classical framework for describing these fields and their propagation (Jackson, 1999;

Griffiths, 2017). In practical accelerator facilities, sensitive control, measurement, communication, and data-processing electronics may coexist with strong RF and electromagnetic environments. Electromagnetic compatibility engineering therefore considers both the generation of unwanted electromagnetic energy and the susceptibility of electronic systems to that energy (Ott, 2009; Paul, 2006).

The experimental problem addressed in this work is the direct observation of electromagnetic interaction with ordinary electronic devices. Because access to an operating cyclotron and calibrated accelerator-RF measurement facilities was not available, a magnetron was selected as a practical microwave source. The magnetron is not treated as a physical replica of a cyclotron. Instead, it is used as an experimentally accessible source whose operation also involves electron motion under simultaneous electric and magnetic fields and resonant microwave generation (Gilmour, 2011).

2. MATERIALS AND METHODS

2.1 Charged-Particle Motion and the Lorentz Force

For a particle of charge q and mass m moving with velocity v in electric field E and magnetic field B, the Lorentz force is:

$$F = q\,(E + v \times B)$$

The electric component can change the kinetic energy of the particle, whereas the magnetic component is perpendicular to the instantaneous velocity and primarily changes the direction of motion. In a uniform magnetic field with velocity perpendicular to B, the magnetic force provides the centripetal force required for circular motion. This relation is the starting point for understanding cyclotron motion and also provides the conceptual connection to crossed-field microwave devices (Griffiths, 2017; Wiedemann, 2015).

2.2 Cyclotron Frequency and Resonance

Equating the magnetic force magnitude $|q|vB$ to the centripetal force mv^2/r gives $r = mv/(|q|B)$. The angular frequency is then $\omega c = v/r = |q|B/m$, and the frequency is $fc = |q|B/(2\pi m)$. For the non-relativistic idealization, the frequency is independent of particle speed, which permits phase synchronization between the particle orbit and the alternating accelerating field (Lawrence & Livingston, 1932; Lee, 2018).

At sufficiently high energies, relativistic effects modify the simple cyclotron relationship. In advanced circular accelerators, the dependence of mass-energy on momentum must be included in the beam-dynamics description (Wiedemann, 2015). The present experiment does not attempt to measure cyclotron frequency directly; the equations establish the theoretical basis for relating charged-particle dynamics to electromagnetic fields.

2.3 Electromagnetic Radiation from Accelerated Charges

A time-varying current distribution and, more generally, accelerated charges produce electromagnetic fields that can carry energy away from the source. The radiative component is described by classical electrodynamics, while the detailed spectrum depends on the acceleration, geometry, energy, and observation conditions (Jackson, 1999). The Poynting vector $S = E \times H$ describes the local direction and density of electromagnetic energy flow. These concepts are useful when interpreting how an electromagnetic source can transfer energy to a receiving electronic structure. Microwaves are electromagnetic waves in the high-frequency portion of the radio spectrum. Engineering treatments commonly consider the microwave regime from roughly hundreds of megahertz to hundreds of gigahertz, with practical boundaries depending on the application (Pozar, 2012). The short wavelength makes reflection, diffraction, transmission-line behavior, resonances, and geometric dimensions particularly important. The exact operating frequency of the magnetron used in the present experiment was not independently measured; therefore, the experiment is described as a microwave-band exposure experiment rather than being assigned an unverified numerical frequency.

3. ELECTROMAGNETIC INTERFERENCE AND ELECTRONIC-CIRCUIT SUSCEPTIBILITY

3.1 EMI as a Source–Path–Victim Problem

Electromagnetic interference can be described by three elements: a source that generates electromagnetic energy, a coupling path through which the energy reaches a receiving system, and a susceptible victim circuit (Ott, 2009; Paul, 2006). In the present experiment the magnetron is the source, free-space propagation and the enclosure form the principal electromagnetic environment, and the electronic devices are the receiving systems.

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Radiated coupling occurs when electromagnetic energy reaches a circuit through space. Conducted coupling occurs when unwanted energy enters through cables, power connections, or other conductive paths. Electronic devices can also experience mixed coupling in which an external field induces currents on cables or enclosure structures and those currents subsequently enter the internal circuit (Ott, 2009; Paul, 2006).

3.2 Frequency as a Susceptibility Variable

Frequency affects the relationship between an incident electromagnetic wave and the physical dimensions and electrical characteristics of a circuit. At microwave frequencies, conductors, cables, PCB traces, apertures, and internal interconnects may participate in coupling and resonance. Experimental studies of MOSFET and CMOS devices have shown that microwave frequency and injected or incident power can alter electrical operating parameters and cause reversible functional upsets (Kim et al., 2004; Kim et al., 2010).

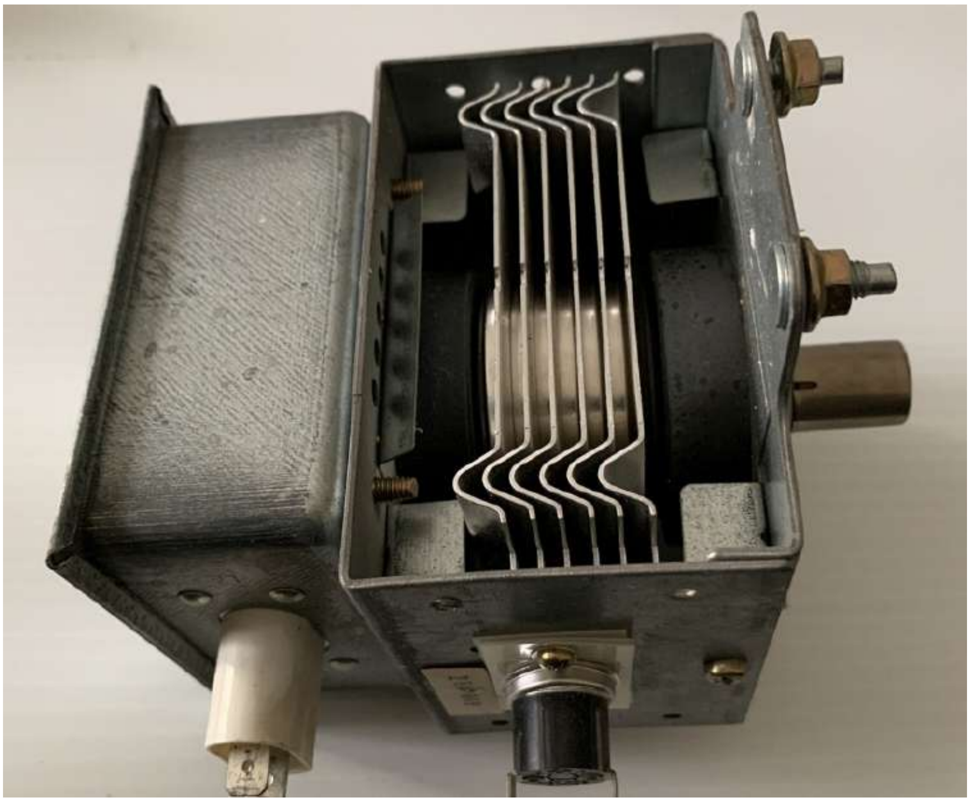

Figure 1. Magnetron used as the microwave electromagnetic-wave source in the laboratory experiment. Original photograph supplied by the researcher.

Figure 1. documents the actual magnetron used in the experimental apparatus. The device was treated as a microwave source whose internal crossed-field electron dynamics and resonant cavities provide the high-frequency electromagnetic output (Gilmour, 2011).

4. MATERIALS AND EXPERIMENTAL APPARATUS

The laboratory experiment was performed in the Physics Faculty laboratory using an accessible magnetron-based microwave source. The main experimental materials were a high-voltage power-supply/transformer unit, high-voltage capacitor, magnetron, electrical connecting leads and clips, metallic enclosure with an aluminum internal surface, and several electronic devices used as receivers.

Component	Role in the experiment	Scientific relevance
Magnetron	Microwave electromagnetic-wave source	Converts electrical input into microwave-frequency oscillation through crossed-field electron motion and cavity resonance.
High-voltage supply / transformer	Provides the electrical operating condition required by the source	Controls the energy supplied to the magnetron; the supply voltage is not the same as the field at the test device.
High-voltage capacitor	Part of the high-voltage source circuit	Stores electrical energy and participates in the magnetron power-supply circuit.
Electrical leads / clips	Electrical interconnection	Provide conductive paths; their geometry can also influence unwanted coupling.
Metallic enclosure with aluminum lining	Reflective electromagnetic environment	Produces reflection and spatial interference of the microwave field.
Mobile phone, camera, calculator, radio, lamp	Test/receiver devices	Provide observable indicators of electromagnetic susceptibility.

5. Experimental Methodology

5.1 Research Design

The study used a laboratory experimental design with a mixed theoretical–experimental approach. The theoretical component was based on established literature in electromagnetism, accelerator physics, microwave engineering, and EMC. The experimental component directly observed changes in electronic-device operation under microwave exposure. The design is best characterized as exploratory and analytical at the laboratory scale because the response was recorded primarily through direct observation rather than calibrated field and circuit measurements.

5.2 Experimental Variables

The principal independent exposure variables were the presence of the microwave electromagnetic field, source-to-device distance, and spatial position within the reflective enclosure. Frequency and field amplitude were treated as physical parameters of the source but were not independently calibrated. The dependent variable was the functional response of the electronic devices, expressed through observable changes such as screen instability, touch-response disturbance, radio noise, abnormal calculator behavior, camera response, and lamp behavior.

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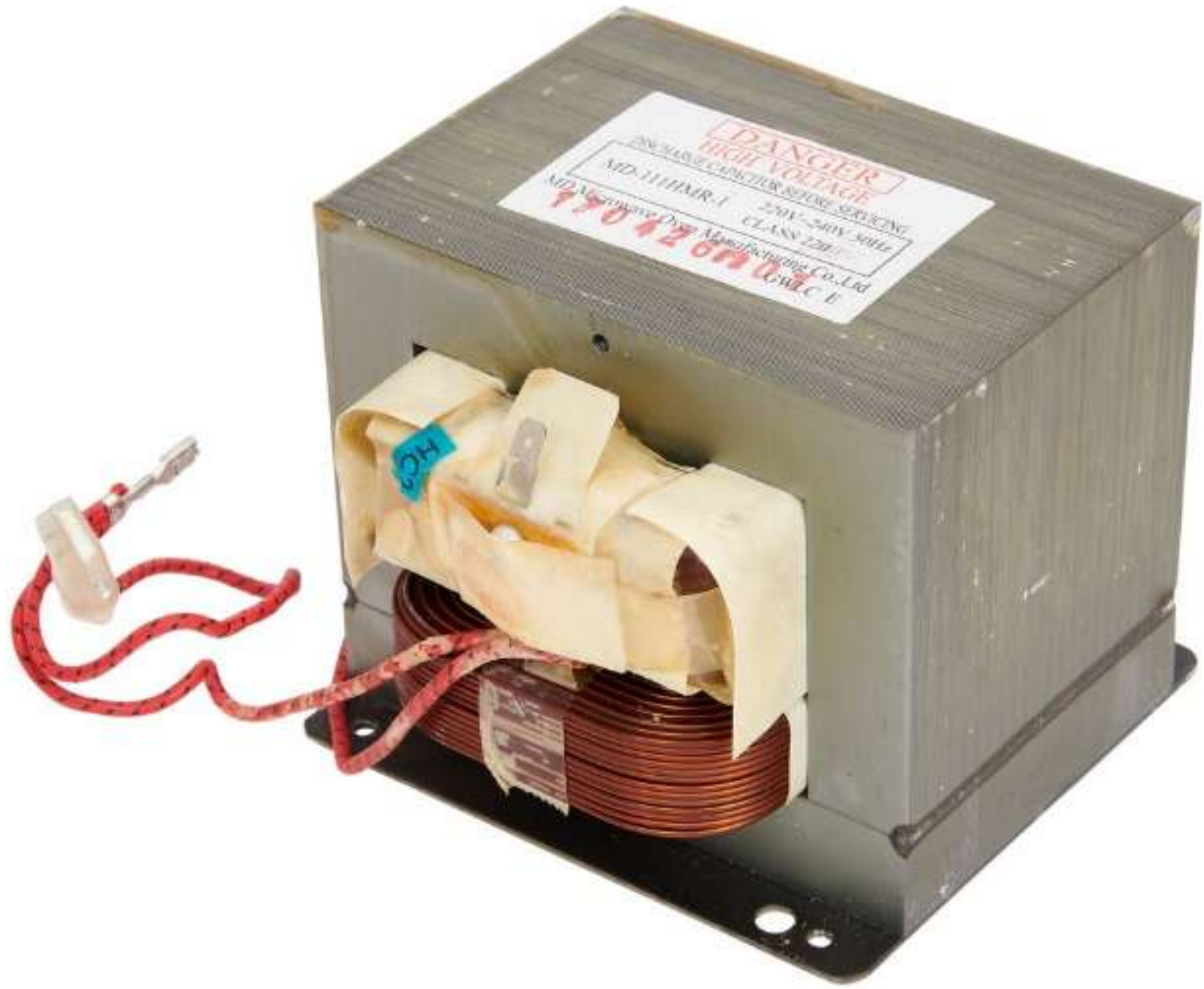

Figure 2. Experimental arrangement of the microwave electromagnetic-wave generation system

Figure 2 shows the high-voltage power-supply/transformer unit, high-voltage capacitor, magnetron, electrical connections, and supporting laboratory components used to generate the electromagnetic field for the exposure experiment**.**

5.3 Exposure and Observation Procedure

- The normal operating condition of each electronic device was checked before exposure.
- The microwave source system was prepared in the laboratory according to the available equipment and safety procedure.
- The devices were initially positioned at approximately 30 cm from the source.
- The devices were observed while the microwave field was present, with attention to visible or functional changes.
- The devices were moved closer to the source to compare the relative severity of the observed response.
- The devices were placed at different positions inside the aluminum-lined enclosure to examine spatial variation.
- The observed responses were documented and interpreted using electromagnetic-coupling and interference concepts.

6. EXPERIMENTAL OBSERVATIONS AND RESULTS

6.1 General Response of Electronic Devices

The experiment showed that microwave exposure produced observable, temporary disturbances in several electronic devices. The mobile phone was particularly responsive: its display sometimes exhibited visible instability or flickering, and at selected positions inside the enclosure the touch interface temporarily became less responsive. The radio exhibited interference/noise, while the calculator and digital camera showed abnormal functional behavior. The lamp also showed changes during exposure. These responses demonstrate that electronic systems with different architectures can exhibit different susceptibility to the same electromagnetic environment.

6.2 Effect of Distance

The reference distance used in the experiment was approximately 30 cm. As the devices were moved closer to the source, the observed disturbances generally became stronger. This observation is consistent with the general expectation that electromagnetic exposure changes with distance from a radiating source. However, because the apparatus operated in a reflective environment and the field was not measured with a calibrated probe, the result should not be fitted to a simple free-space inverse-square law.

6.3 Device-to-Device Differences

The devices did not respond identically. This difference is scientifically important because susceptibility depends on circuit architecture, shielding, cable geometry, internal resonances, operating frequency, filtering, grounding, and semiconductor technology. The observations therefore support a system-level susceptibility interpretation rather than the assumption that all electronic circuits respond in the same way.

6.4 Summary of Observed Responses

Device	Observed response	Relative interpretation	Evidence type
Mobile phone	Screen instability/flickering; temporary touch disturbance at selected positions	Higher apparent susceptibility at some field locations	Direct visual/functional observation
Radio	Noise or abnormal audio behavior	Electromagnetic coupling into receiving circuitry	Direct observation
Calculator	Abnormal display/operation	Temporary circuit disturbance	Direct observation
Digital camera	Abnormal response during exposure	Temporary disturbance of electronic operation	Direct observation
Lamp	Change/flicker during exposure	Interaction of field with electronic/driver circuitry where present	Direct observation

7. DISCUSSION

The results support three principal conclusions. First, the observed device disturbances demonstrate that microwave electromagnetic exposure can interact measurably with practical electronic circuits. Second, distance influences the severity of the observed response, consistent with changes in electromagnetic exposure. Third, the aluminum-lined enclosure produces a spatially non-uniform electromagnetic environment, and the strongest observed device responses occurred at selected positions that are consistent with regions of enhanced field due to interference.

The role of frequency should also be emphasized. The frequency determines wavelength and therefore the relationship between the electromagnetic field and the physical dimensions of the enclosure, device, cables, and internal circuit structures. In microwave systems, these dimensions can become electrically significant, so small changes in geometry or position can alter coupling and resonance behavior (Pozar, 2012). This provides a theoretical explanation for why the same device can respond differently at different positions.

The role of voltage must be interpreted at two levels. At the source, high voltage supplies the energy required for magnetron operation. At the receiving circuit, the relevant quantity is the electromagnetic field-induced voltage/current coupled into the circuit. The present experiment demonstrates the latter only qualitatively; it did not directly measure induced voltage. This distinction prevents an incorrect inference that the high-voltage label on the source directly represents the electrical stress experienced by the test devices.

The experimental findings are also consistent with the general EMC principle that electronic susceptibility is not determined by field amplitude alone. The coupling path, orientation, shielding, cable configuration.

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8. CONCLUSION

This study presented an experimental investigation of microwave electromagnetic interaction with electronic circuits within a framework motivated by cyclotron physics. The theoretical analysis established that charged-particle motion in electric and magnetic fields is governed by the Lorentz force and that cyclotron operation depends on the synchronization of particle motion with an RF accelerating field. The study then used a magnetron as a practical microwave source because it provides an experimentally accessible realization of charged-electron motion in crossed fields and resonant microwave generation.

The laboratory experiment employed a high-voltage source system, high-voltage capacitor, magnetron, electrical connections, and an aluminum-lined metallic enclosure. At an initial distance of approximately 30 cm, temporary functional disturbances were observed in several electronic devices, and the disturbances generally increased as the devices were brought closer to the source. Within the reflective enclosure, the response varied with position, which is consistent with interference between incident and reflected microwave fields.

The most important scientific interpretation is that the electromagnetic field can couple to electronic structures and induce unwanted electrical disturbances. The observations agree qualitatively with established EMC theory and with previous experimental studies of microwave susceptibility. At the same time, the study deliberately distinguishes functional interference from permanent damage and avoids attributing a specific microscopic failure mechanism to the consumer devices without direct measurements.

The work therefore provides a useful experimental bridge between accelerator physics, microwave physics, and EMC. Its principal value is not the production of a high-power source but the demonstration and analysis of a physical chain that can be measured more rigorously in future research: electromagnetic generation, propagation, reflection, spatial interference, coupling into electronic circuits, and functional response.

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