MODELLING AND SIMULATION OF AXIAL-VIRTUAL CATHODE OSCILLATOR USING MATLAB SIMULINK

AHMED ABDALLA MOUSTAFA HUSSEIN

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

This thesis presents the modelling and simulation of an Axial-Virtual Cathode Oscillator (Axial-VIRCATOR), using the MATLAB Simulink software package. One dimensional model of VIRCATOR has been implemented by using mathematical model based on Child-Langmuir Law that describes the charge, charge density, current, voltage, power and efficiency of the VIRCATOR as a function of its mechanical parameters. Hence, the Axial-VIRCATOR model was chosen where its mechanical parameters such as cathode radius, anode-cathode (A/K) gap and tube diameter were evaluated. In order to adjust the tuning characteristics of the VIRCATOR tube which need to achieve the optimal output microwave power, energy and efficiency, the operation's frequencies were chosen carefully to be 4.0, 6.0, 6.3 and 8.0 GHz. Thus are the most crucial of factors to be investigated in this work. Other quantities such as the beam current, beam radius, cathode radius and transparency were derived in the analytical model and found to be in agreement with the simulation results which influencing the power efficiency, such as the anode-transparency factor T_a and the dispersion factor. Analysis results showed significant improvement of the efficiency, output power and the radiated energy of microwave output which are 43.94%, 11.64 GW and 2.4 Joules (1.5×10^{13} MeV) respectively. This was achieved by carefully choosing the resonance characteristics of the VIRCATOR tube especially the influence of the relativistic component in the charge density solution, which shows a close approximation to the input current closest to the relativistic beam. The results showed by the simulation were compared to an up to date experimental publications and found to be compatible. An error calculation criterion has been implemented which shows minimum error values of -0.01 dB for the input voltage of 600 kV and this was agreed with the relativistic solution considered in this work.

ABSTRAK

Tesis ini membentangkan pemodelan dan simulasi Axial-Virtual Cathode Oscillator (Axial-VIRCATOR), menggunakan pakej perisian MATLAB Simulink. Model satu dimensi VIRCATOR telah dilaksanakan menggunakan model matematik berdasarkan Hukum Child-Langmuir yang menerangkan cas, ketumpatan cas, arus, voltan, kuasa dan kecekapan VIRCATOR sebagai fungsi parameter mekanikalnya. Oleh itu, model Axial-VIRCATOR telah dipilih di mana parameter mekanikalnya seperti jejari katod, jurang anod-katod (A/K) dan diameter tiub telah dinilai. Untuk melaraskan ciri-ciri penalaan tiub VIRCATOR yang perlu mencapai kuasa gelombang mikro keluaran optimum, tenaga dan kecekapan, frekuensi operasi telah dipilih dengan teliti untuk nilai-nilai 4.0, 6.0, 6.3 dan 8.0 GHz. Kesemua itu adalah faktor paling penting yang telah dikaji dalam kerja ini. Kuantiti lain seperti arus pancaran, jejari pancaran, jejari katod dan ketelusan diperolehi dalam model analitikal dan didapati selaras dengan keputusan simulasi yang mempengaruhi kecekapan kuasa, seperti faktor ketelusan anod *Ta* dan faktor serakan. Keputusan analisis menunjukkan peningkatan yang ketara bagi kecekapan, kuasa keluaran dan tenaga terpancar keluaran gelombang mikro iaitu 43.94%, 11.64 GW dan 2.4 Joule (1.5x10 13 MeV) masing-masing. Ini dicapai dengan pemilihan teliti ciri resonans tiub VIRCATOR terutamanya pengaruh komponen relativistik untuk solusi ketumpatan cas, yang menunjukkan penganggaran kepada arus masukan yang terhampir dengan pancaran relativistik. Keputusan yang ditunjukkan oleh simulasi telah dibandingkan dengan keputusan secara eksperimen yang terkini dan didapati kedua-duanya mempunyai keserasian. Kriteria pengiraan ralat telah dilaksanakan yang menunjukkan nilai ralat minimum -0.01 dB untuk voltan masukan 600 kV dan ini menunjukkan kesetujuan dengan penyelesaian relativistik yang dipertimbangkan dalam kerja ini.

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LIST OF ABBREVIATIONS

HPM	-	High Power Microwave
EMC		Electromagnetic compatibility
EMI	-	Electromagnetic Interference
EMP	-	Electromagnetic Pulse
HEMP	-	High Altitude Electromagnetic Pulse
N-NEMP	-	Non-Nuclear Electromagnetic Pulse
TWT	-	Travelling Wave Tube
BWO	-	Backward Wave Oscillator
VIRCATOR	-	Virtual Cathode Oscillator
RDG	-	Relativistic Diffraction Generator
FEL	-	Free Electron Laser
INIPIC	-	Institute for Nuclear Problem Particle In Cell Code
DED	-	Direct Energy Devises
PFL	-	Pulse Forming Line
MWCG	-	Multi- Wave Cherenkov Generator
MILO	-	Magnetically Insulated Transmission Line Oscillator
TTO	-	Transient Time Oscillator
CARM	-	Cyclotron Auto-Resonance Maser
EEE	-	Explosive Electron Emission
SCL	-	Space-Charged-Limited
A/K	-	Anode-cathode

LIST OF SYMBOLS

GHz	-	Giga Hertz
KJ	-	Kilo Joule
MW	-	Mega Watt
GW	-	Giga Watt
kV	-	Kilo volt
MV	-	Mega Volt
S	-	Second
A	-	Ampere
kA	-	Kilo ampere
$E_{th.}$	-	The threshold energy
V	-	the anode-cathode voltage
cm	-	Centimeter
J_{SCL}	-	the space-charge current density
ε_0	-	the free space permittivity
e	-	The electron charge
m	-	The electron rest mass
d	-	the anode-cathode gap
K	-	The relativistic constant $K = e/(mc^2)$
γ_0	-	Lorentz factor
I_{pinch}	-	The pinching current
I_c	-	The critical current
T_a	-	The anode-transparency
I_b	-	The injected beam current
f_v	-	The oscillating frequency
f_p	-	The relativistic plasma frequency
n_b	-	The beam density
ω_p	-	The relativistic angular frequency
v_0	-	Electron initial speed at the anode
$P(t)$	-	The power function
P	-	The average power radiated

p_{BW}	-	The radiated power in the desired band
α	-	The particle accumulation rate
$x(t)$	-	The particle position function
$\bar{x}$	-	The mean position
ε_0	-	The space permittivity
J_b	-	The electron beam current density
ϵ_a	-	The dispersion factor
ESD(f)	-	The energy spectral density
η	-	Energy/power efficiency
E_{in}	-	The input energy
$\rho(x)$	-	The charge density
$\varphi(x)$	-	The potential function
F	-	The Hypergeometric Function

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CHAPTER 1

INTRODUCTION

1.1 Research background

High Power Microwave (HPM) generation has been considerable interest recently by many countries. For example, in the USA during year 2000, high-power microwave (MURI) project which involved 9 universities, 3 private companies, and 3 research institutions has been ended. However, due to it highly potential applications, it has been extended for another five years [1]. Similar efforts are carried out by many other countries like China, Russia, Great Britain, France, Germany, Sweden, South Korea, Taiwan and Israel [2]. Many pieces of the research over the past 25 years were related to the technologies of producing compact power systems driving HPM sources for both civilian and military applications [1-9].

Electromagnetic compatibility (EMC) is a branch of physics related to the generation of HPM which concerned with the generation, transmission, and reception of electromagnetic energy. On the other hand, electromagnetic interference (EMI) appeared a hundred years ago with the presence of applications that covers the whole frequency band [3]. EMC has many aspects and the Electromagnetic Pulse (EMP) is one of the main aspects of it. Many researches explain the threat of EMP to the electronic equipment causing destruction for both military and civilian systems [9,10,11]. Concurrently, many techniques developed to protect against the EMP threat such as filters, voltage limiters, spark gaps and arrestors which are known as shielding [4]. EMP usually results from high energy action such as a nuclear fission explosion within 25-40 km of its center, or high above the ground produces High Altitude Electromagnetic Pulse (HEMP). Another type of EMP can be generated without the use of nuclear reaction known as Non-Nuclear (N-NEMP) which is the main focus in this research.

The term Microwave refers to an alternating current signal with a frequency range from 300 MHz to 300 GHz and a wavelength corresponding to the frequency range from 1 mm to 1 m respectively [6]. The term high power refers to pulses exceeded 100 MW in peak power. Microwave was first generated in the lab by Hertz in the 1880s. Radio waves was used at lower frequencies in the early 20th century with the advent of gridded tubes. In the 1930s, several investigations realized that resonant cavities can obtain higher frequency ranges. The first cavity HPM source invented was the Klystron in 1937, then a faster activity during World War II, includes the extrapolation of the magnetron and the invention of the Travelling Wave Tube (TWT) and the Backward Wave Oscillator (BWO). In 1960s, the cross-field amplifier was invented. During 1970s, a strong need of low power, but extremely compact, solid-state based microwave source exist. Since 1950s, experiments were made to control thermonuclear fusion for energy production led to the understanding of wave particles interaction and the plasma behavior which led to the development of a special type of high average power microwave frequencies as high as 100 GHz. In 1960s, electrical technology introduced pulsed power systems that can produce a current exceeds 10 kA at 1 MV such as Gyrotron. Figure 1.1 shows the historical origins of high power microwave [7]

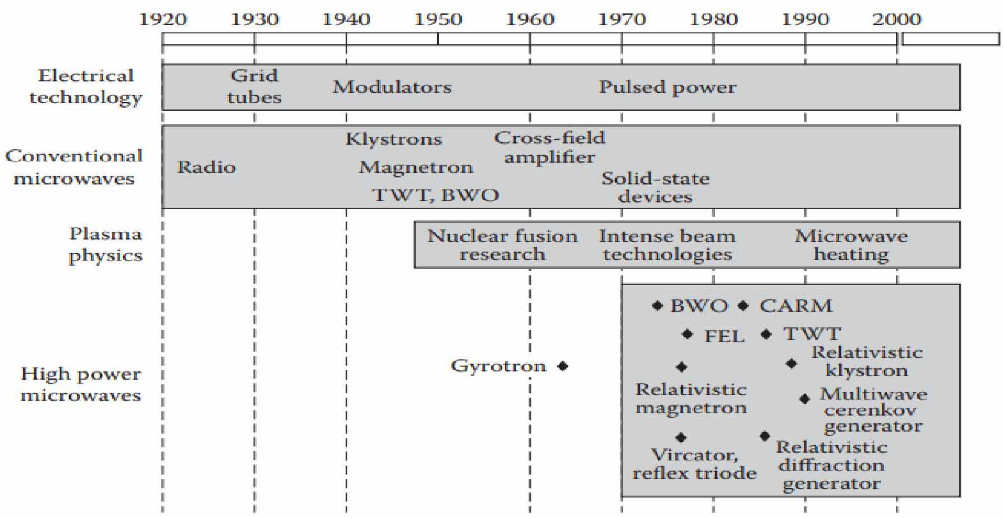

Figure 1.1 Historical origins of high power microwave [7]

The first HPM source that use a conventional microwave tube was Backward Wave Oscillator (BWO) and the Travelling Wave Tube (TWT), in these devices, the high power used is a relativistic beam produced from the interaction between the operating current and a strong beam field coupling, relativistic beam means electron energies greater than 510 k eV rest energy. The main focus in this research will be the Virtual Cathode Oscillator (VIRCATOR). VIRCATOR is an electronic vacuum microwave device, which used as a pulse HPM source. It is characterized by a simple mechanical structure, lack of external magnetic field and tunable frequency (typically 1-10 GHz) [19]. The first time VIRCATOR was observed by Irving Langmuir, who analyzed the behavior of electron beam accelerating between two electrodes [20].

The historical background of HPM until the1990s, focused the higher frequency levels on the higher power levels. Multi-wave Cerenkov and the Diffraction Generator (RDG) in Russia achieved a world record based on a large interaction region. In the USA, the Relativistic Magnetron and Klystron at lower frequencies were successful. All of these efforts success is the production of a peak microwave in terms of the Pf^2 . Figure 1.2 shows the development of microwave in terms of Pf^2factor where HPM devices began with $Pf^2 \sim 1$ and have progressed upward in order (almost three orders in 20 years). Free Electron Laser (FEL) is found to be the highest device in terms of this factor [8].

But why f^2 ?. Pf^2 scaling for a microwave source gives evidence that the power is proportional to the resonant frequency of the cavity which in turn is proportional to the wavelength, and the cross-section of the waveguide limits the breakdown of the electric field. Another reason, that the power density of microwave transmitted on the target is proportional to the Pf^2 therefore, parameters for HPM source ranking and power beaming over a distance which is still a point of research gap that require more investigations. Figure 1.3 shows the peak power of different HPM sources taking into account the values of the quality factor Pf^2 [9].

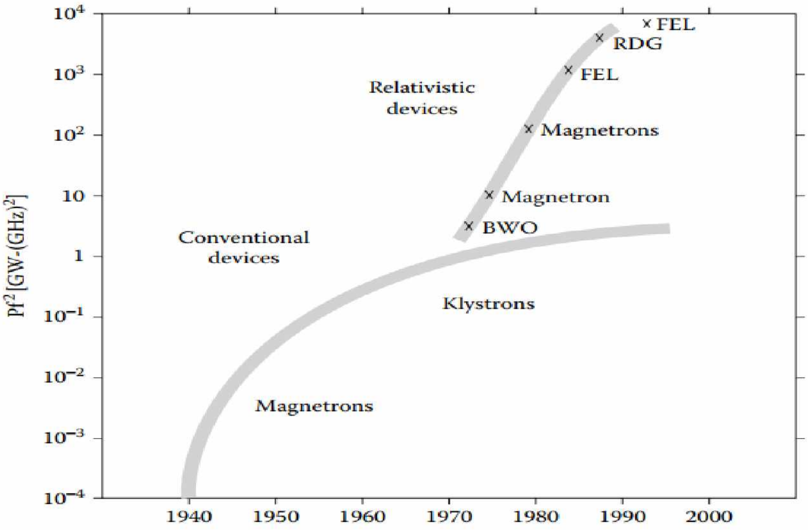

Figure 1.2 Growth of Microwave devices in terms of quality Factor Pf2 [8]

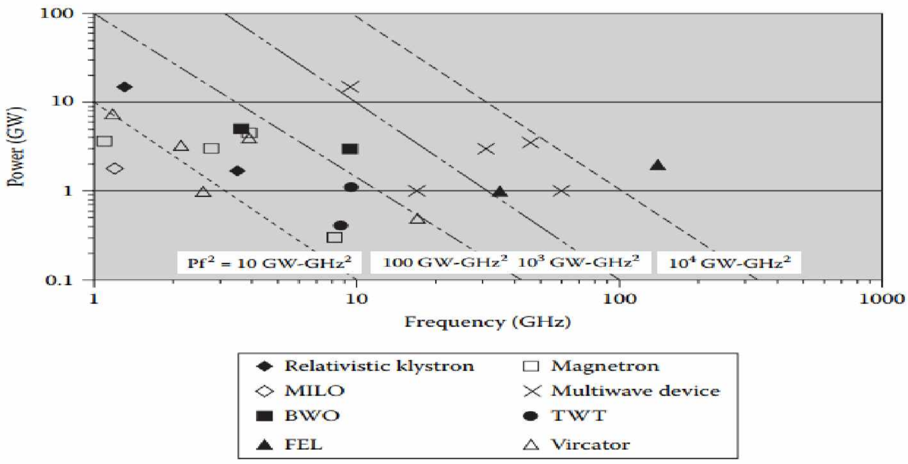

Figure 1.3 Shows the peak powers of different HPM sources. Values of quality factor vary over several orders of magnitudes. [9]

The peak power efficiency is another issue that limits HPM sources. The peak power efficiency is defined as the ratio between the radiated microwave power to the power of the electron beam and is related to the energy efficiency as well. The energy efficiency is defined as the microwave pulse energy ratio to the electron beam energy. Several researches aimed at the fact that energy and power efficiency are usually much lower than what's expected due to the failure of sources to fill out the resonance conditions at very high power [10]. Figure 1.4 shows a comparison of the peak power of a device plotted against its average power. Conventional tubes extend in wider ranges and that's because such kind of tubes developed for the desired applications of particle accelerators and radar applications.

The early history of HPM ended by 1990 with a clear realization that devices were fundamentally limited above the peak power of 10 GW and pulse energy of 1 kJ. These efforts are added benefit of three-dimensional computational modelling on different HPM systems. Therefore, that was the key element to introduce HPM simulation using one of the powerful tools MATLAB SIMULINK to analyze parameters that could lead to the decrease in pulse length as a reassessment of the way the HPM community has been developing its resources. MATLAB simulate the electrodynamic electron-plasma interaction which is the key factor and the source of kinetic energy passed into the collector of the source. [11]

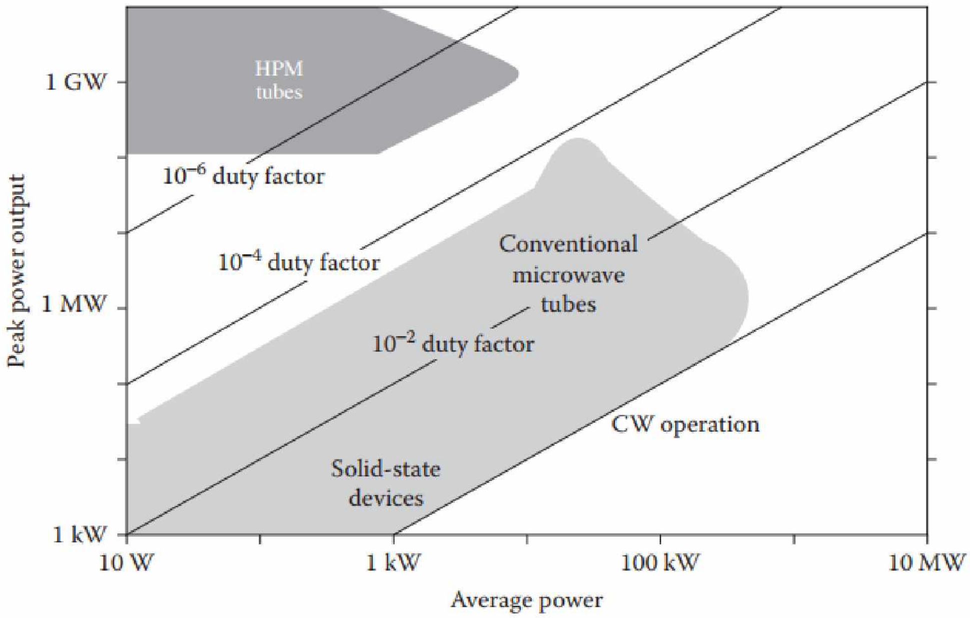

Figure 1.4 Peak vs. average power for Microwave sources with duty factor [10]

1.2 Problem statement

Virtual Cathode Oscillator (VIRCATOR) was a successful source of microwave comparing to the other microwave sources that might be driven by Marx Generator. This success is due to its ability to operate without a guiding magnetic field. Its short operation region is enhanced tunability of frequency of operation. VIRCATOR high output power and simple design make it preferable for the applications of EMP weapons and microwave power transmission [12,13]. However, the lower efficiency and frequency instability were always disadvantages that many researchers are trying to investigate. By using the advantage of computer simulation, for example, the microwave power generated from a conventional axial VIRCATOR was 571 MW with an efficiency of approximately 20% increased to 835 MW with efficiency up to 46 % using a cone- shaped reflector [14]. Researchers were capable of increasing VIRCATOR efficiency, by setting resonant conditions of the beam energy to high power microwave conversion, but this increases the efficiency of VIRCATOR by only 6-7% which is still not sufficient [15,16] .

Another issue with VIRCATOR which is the main reason for low efficiency is the shortening of the pulse length particularly the cathode plasma expansion and the influence of the beam drift velocity on the power and energy efficiency which is strongly dependent of the geometrical dimensions of VIRCATOR [17]. Many researchers used self-developed codes to do a simulation of the problem such as INIPIC (Institute for Nuclear Problem Particle In Cell Code) which combines the finite-difference formulation of Maxwell's equations and the finite size particle method [18]. This method is less well suited for the dynamic analysis of electron plasma interaction. On the other hand, Simulink can handle this issue easily, since it was a faster simulation tool compared to INPIC.

In this research, a model explaining the relation between the geometrical parameters of the VIRCATOR and its radiated energy is proposed. How the parameters of the VIRCATOR can be chosen, such as the radiated energy maximizes at a given frequency? Based on this modelling, a VIRCATOR prototype is proposed. The analysis for optimizing electrical and mechanical design is performed and the main key of VIRCATOR drawback which is the transformation of electron energy into microwave signal will be overcome. The dynamic performance of VIRCATOR was evaluated using MATLAB package utilizing Simulink block for a complete system simulation.

VIRCATOR is a promising device for the application under investigation which focus especially on the E-bomb and direct energy weapons. The VIRCATOR model should be chosen first to implement its mechanical characteristics linked to its electrical characteristics such as the peak power per pulse, frequency range of output power and energy. All of these parameters are implemented into the MATLAB programming and incorporated with Simulink as Matrix arrays simulation tool.

1.3 Research objectives

The VIRCATOR parameters analysis will give more understanding about the mechanism of its operation which is an essential component of HPM system and to achieve this goal, the following objectives are set:

i. To model a chosen VIRCATOR prototype using Child-Langmuir current density relativistic solution which relate its mechanical and electrical characteristics.
ii. To simulate the VIRCATOR model which focus to the energy and power efficiency by manipulating the frequency, output voltage, output power, and peak power per pulse using MATLAB Simulink.
iii. To analyze VIRCATOR dynamic performance related to the output power, Child-Langmuir solution for current density, efficiency due to the cathode transparency.

1.4 Scope of the research

This research is focus on analyzing the pulse peak energy and pulse repetition rate which are the most effective factors for Direct Energy Devises (DED) and by analyzing VIRCATOR operation parameters such as the input current, the critical current, and input voltage in a given frequency range. By understanding the operation process and the expected damage that could be produced, therefore it could help the decision maker regarding the shielding requirements to protect the infrastructure of modern civilizations hubs against the risk EMP weapons. The major advantage is to analyze one enabling technology taking into account standards of EMC and utilizing the powerful tool of MATLAB Simulink. The system simulation results will be compared with experimental results for performance assessment.

1.5 Significant of study

Most simulation researches on VIRCATOR was carried out using INPIC or SPICE computer tools while in this research MATLAB Simulink is used to simulate the dynamic system with matrix-based computation that solves numerical problems in a fraction of time compared to other software programs. MATLAB is also used to find a solution in the field of signal processing and control systems with a higher speed and capability as compared to the previous work in this field.

VIRCATOR simulation results will provide a realistic assessment of the system power and energy efficiency and trying to find an explanation of the shortening pulse length at high power ranges.

Four Axial-VIRCATOR models are considered to imitate the effect of changing the independent parameters of VIRCATOR which are the operational frequency, The draft-tube length, and the anode transparency. And to study how these fixed parameters will affect the electrical parameters of VIRCATOR under changing of the input voltage, the cathode/anode gap and recording the optimum values yields to improving power, energy and efficiency of VIRCATOR.

Analysis of the simulation will be compared with the experimental results which will provide the necessary data to estimate the improvement of VIRCATOR operation especially the leakage of efficiency which is the main question in this thesis. In **chapter 2** a literature review of VIRCATOR as HPM source will be provided with all the necessary theoretical background. **Chapter 3** will introduce the Methodology used to optimizing power, energy and efficiency of Axial-VIRCATOR and explaining the simulation steps. **Chapter 4 put** highlight on the main findings of this thesis and a discussion of these results will be placed in **Chapter 5**.

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LIST OF PUBLICATIONS

[1] Has Been **ACCEPTED** and will be proceeded to publication in the Proceedings Science and Mathematics (Online ISSN: 2756-8857).