Investigations on Different Aspects of the Magnetically Insulated Line Oscillator (MILO) and Bi-frequency MILO

Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

By

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ACKNOWLEDGEMENTS

Foremost, I would like to express my immense gratitude to my supervisors Prof. P. K. Jain and Dr. Smrity Dwivedi for their excellent guidance and motivation. The completion of this research work is truly an outcome of their constant untiring support, valuable ideas, and suggestions during my research work. The insightful discussions with them always provided me great enthusiasm. I could not have imagined having better advisors and mentors for my research work.

I wish to extend my sincere gratitude towards my research performance evaluation committee (RPEC) members, Dr. Somak Bhattacharyya and Prof. R. Mahanty for their encouragement and insightful comments. I also thank to all faculty members for their kind cooperation and encouragement during this journey.

My special thanks to Dr. V. Nallasamy, Dr. M. S. Chauhan, Dr. Gargi Dwivedi, Dr. Amit Arora, Dr. M. V. Swati, Dr. Manpuran Mahto, Dr. Siva Venkateswara Rao V., Dr. Vikram Kumar, Dr. Rajan Agrahari, Dr. A. P. Singh, and Dr. Anshu Sharan Singh for their valuable assistance from personal to the technical level.

I am very much thankful to many research scholars of the CRMT laboratory for providing a stimulating and friendly environment. My thanks go to Mr. Prabhakar Tripathi, Mr. R. K. Singh, Mr. M. A. Ansari, Mr. Akash, Mr. Vineet Singh, Mr. Sambit, Mr. Dipti, Mr. Nilotpal, Mr. Nishit, Mr. Soumjit, Mr. V. V. Reddy, Mr. V. Veera Babu, Mr. G. Venkatesh, and Mr. S. G. Yadav.

My thanks and sincere appreciations also go to all staff members of the CRMT laboratory, especially to Mr. Rajesh Kr. Rai for their kind co-operation.

I also thank my colleagues, Mr. Amit, Dr. Aman, and Mr. Ratan, for providing a fun-filled environment.

I deeply admire my Brothers, Sisters, and my close friends Mr. Shashikant and Mr. Vikash for their continued support and encouragement. They are the source of strength for me and remain an invaluable asset to me.

I would like to express my special thanks to my wife Laxmi for her patience and continued support. She supported me a lot during these times.

Finally, I hearty express sincere thanks to my parents Shri. Biru Roy and Smt. Gayatri Devi. I wish to express indebtedness to them, for their unconditional love, extreme patience, and constant support over the years. They provide me the strength and confidence to attain this task.

Above all, I bow my head before almighty Lord Vishwanath for providing me the strength and courage in completing my research work.

Date: ***(Arjun Kumar)***

Dedicated
To
My Supervisor
and My Family

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LIST OF ABBREVIATIONS

Abbreviation	**Full form**
HPM	High power microwaves
RF	Radio Frequency
PRF	pulse repetition frequency
DEW	Direct energy weaponry
EM	Electromagnetic
TWT	Traveling wave tube
RBWO	Relativistic backward wave oscillator
MILO	Magnetically insulated line oscillator
GHz	Giga-hertz
MHz	Mega-hertz
GW	Giga-watt
MW	Mega-watt
Ns	Nano-second
RKO	Relativistic klystron oscillator
RKA	Relativistic klystron amplifier
CRM	Cyclotron resonance masers
FEL	Free Electron Laser
SWS	Slow-wave structure
TM	Transverse Magnetic
MW	Mega-watt
SCO	Split cavity oscillator

TE	Transverse Electric
EEE	Explosive electron emission
CTL	Coaxial transmission line
UHF	Ultrahigh frequency
RBF	Relativistic Brillouin flow
VCO	Virtual cathode oscillator
PIC	Particle-in-cell
HEM	Hybrid electromagnetic
HE	Hybrid electric
FFT	Fast Fourier Transform
AC	Alternating Current
DC	Direct Current
TTO	Transit time oscillator
BFMILO	Bi-frequency magnetically insulated line oscillator
TGR	Temporal growth rate
SCW	Space charge wave
Cm	Centimeter
Mm	Millimeter
kV	Kilo-volt
kA	Kilo-ampere
TEM	Transverse Electromagnetic

LIST OF SYMBOLS

Symbol	**Details**
v_e	Electron velocity
v_p	phase velocity
L_e	Equivalent series inductance per unit length
C_e	Equivalent shunt capacitance per unit length
G_e	Equivalent shunt conductance per unit length
R_e	Equivalent series resistance per unit length
r_c	Cathode radius
r_d	Disc inner radius
r_w	Outer wall radius
L	Periodicity
T	Thickness
E	Electric field
H	Magnetic field
β_n	Axial propagation constant
ω	Angular frequency
γ_n	Radial propagation constant
k	Free space propagation constant
J_0	Bessel functions of 1st kind with zero order
Y_0	Bessel functions of 2nd kind with zero order
ρ_s	Surface charge density
I_z	Axial current
V	Voltage
J_z	Axial current density
c	Speed of light
F	Frequency

A_z	Vector potential
μ	Permeability
ε	Permittivity
I_θ	Azimuthal current
Z_0	Charatecteristic impedance
$f_1\{x, p, t\}$	RF distribution function
ς_n	velocity shifted frequency
Γ_n^*	Radial beam parameter in presence of beam
ω_p	Plasma frequency
Q_{int}	Internal quality factor
Q_{ext}	External quality factor
Q_0	Loaded quality factor
P_0	Initial injected power
ρ	Complex reflection coefficient
L_{IC}	Equivalent series inductance per unit length for Interaction structure
C_{IC}	Equivalent shunt capacitance per unit length for Interaction structure
W_{nm}	Inductance factor
P_{nm}	Capacitance factor
$L_{ch}(z)$	Equivalent series inductance per unit length for tapered choke section
$C_{ch}(z)$	Equivalent shunt capacitance per unit length for tapered choke section
L_{ext}	Equivalent series inductance per unit length for extractor section
C_{ext}	Equivalent shunt capacitance per unit length for extractor section
L_{cx}	Equivalent series inductance per unit length for coaxial section
C_{cx}	Equivalent shunt capacitance per unit length for coaxial section
Z_{IC}	Impedance of interaction structure
Z_{ext}	Impedance of extractor section

$\Gamma(z)$	Nominal propagation constant
$K(z)$	Nominal characteristic impedance
$q_v(z)$	Reflection coefficient at tapered cathode section
$C_{E.G}$	Capacitance of the extractor gap
$E_{E.G}$	Electric field at the extractor gap
$\sigma_{E.G}$	Charge per unit length at extractor
Z_{stub}	Impedance of stub
L_{stub}	Inductance of stub
l_{stub}	Length of stub
λ	Wavelength
λ_g	Guided wavelength
l_T	Length of tapered cathode
$\hat{v}_z$	Axial drift velocity
γ	Relativistic factor
P_z	Axial momentum
n_e	Charge number density
r_e	Electron beam radius
η	Normalized factor
$\delta(r-r_e)$	Delta function
I_A	Alfven current
P_θ	Azimuthal momentum
J_θ	Azimuthal current density
γ_n^*	Radial propagation constant in presence of electron beam
v_{slow_sc}	Slow space charge velocity
f_i	Imaginary value of frequency
f_r	Real value of frequency
I_a	Anode current
I_{cr}	Critical current

B_c	Cut-off magnetic field
V_H	Hull cut-off voltage
V_{BH}	Buneman-Hartee voltage
e	Electron charge
m_0	Electron mass
χ_{np}	Modal root of the nth order Bessel–Neumann combination
dB	Decibel

PREFACE

High-power microwave (HPM) has been very popular in the microwave community due to its various civilian and military applications. The generation of RF in millimetre-wave ranges and dual-frequency generation through a single HPM device drag the attention of researchers and academia around the world for R&D in this domain. HPM source is the device that can generate RF power more than 100 MW in a frequency range from 1-100 GHz. HPM application domains are mainly in communication, Radar, UWB, Power beaming, linear colliders, fusion heating, and indirect energy weapons (DEW). The whole process of HPM generation and application uses different sub-systems starting with prime power supply and followed by pulsed DC power formation, a microwave source, mode converter, and antenna. These different sub-systems of the whole HPM system have a unique role in the whole process of RF generation and application. Microwave or HPM source is the main sub-system in the whole microwave generation process. The different HPM sources which can generate RF power are relativistic magnetron, relativistic klystron, relativistic backward wave oscillator, relativistic gyrotron devices, Vircator, Reltron, and magnetically insulated line oscillator (MILO). The different radiation process followed by these HPM sources is mainly classified as Cherenkov radiation, transition radiation, and Bremsstrahlung radiation. This work is mainly based on the HPM source, MILO, which uses the Cherenkov radiation process. Comparing the other HPM source, the MILO does not require any external magnetic field which makes it compact, lightweight, and compatible to use on different mobile platforms.

MILO is a crossed-field high power microwave device that is similar in operation and theory of magnetron. It operates by combining the technology of magnetically insulated electron flow and slow-wave tubes. Microwave oscillator which requires an external DC magnetic field employs two DC power sources for exhibiting magnetic insulation and also gives rise to electrical breakdown as higher voltages are approached. These oscillators are having a very high inherent impedance that severely limits the power level at which the oscillator will operate. Thus, for efficient operation at higher power levels, it would be desirable to have an oscillator that will operate at the lower impedance and also eliminate the problem of voltage matching. To overcome the above problems, MILO has been used, in which the required magnetic field is supplied by the electron-beam current itself, rather than by a separate magnet and thus makes the device more compact and lightweight.

The designing improvement of MILO to avoid some critical issues like pulse shortening problem, asymmetric mode generation and mode competition, shot-to-shot reproducibility, the requirement of high pulse rate frequency and long life of cathode are still consider as a challenge for device development. The performance improvement of MILO and bi-frequency MILO is the prime work to be done. In order to carry out the aforementioned work, the author has considered the optimization of the MILO device sub-section and impedance matching between different sections using an equivalent circuit approach. Further, the study of beam-wave interaction for the generation of bi-frequency through MILO device has also been taken as the objective for current work.

The author, from time to time, has reported the present work part-wise at national and international conferences as well as in reputed journals, namely, IEEE transaction on plasma science.

The author will consider his modest effort a success if it proves to be useful in the design of MILO and bi-frequency MILO**.**