CHAPTER-7

Summary and Conclusions

7.1 Limitations of the Present Study and Scope for the Future Work

In recent times, high power microwaves (HPM) applications for civilian and military has led to the focussed efforts on the research and development of the HPM sources. HPM devices are also being used as Directed Energy Weapons (DEW). The conventional microwave tubes and semiconductor based sources and amplifiers cannot produce high power microwaves. In the case of HPMs, different electron beam devices are under development to improve the power level and frequency range. The development of HPM devices has emerged in recent years as a newer technology and pushed the conventional microwave device physics in a new direction. In these devices, high voltages are used to produce the relativistic electron beam and the electron energies are comparable or greater than 510 keV (rest energy of an electron). Nevertheless, lot of research related o perplexing issues are still to tackle for the improvement of the device performance. It requires the study of the performance improvement techniques for conventional HPM sources and their developments. Further, an extensive renewed interest has been provoked in the research and development of HPM sources in view of their potential capabilities of producing high RF power in terms Giga-Watts (GW) level at microwave frequencies for non-lethal applications. In recent years, many HPM sources including relativistic magnetron, reltron, vircator, MILO, relativistic backward wave oscillator (RBWO), gyrotron, etc, have been keeping on competing to bridge the technological gap that could not be done by the conventional microwave tubes. MILO is an M-type crossed-field, compact HPM device that can generate giga-watts of peak power at the microwave frequency range from L to Ku band. The salient feature of MILO is that the generation of self-magnetic field due to the high electron current flow in the circuit so that electrical breakdown between cathode and anode is prevented. Thus, there is no requirement of external DC magnetic field and the device is able to handle extremely large input power (more than ten's of gigawatts) at modest applied voltages (several hundred kilovolts). MILO has emerged out as a relatively new HPM device which is compact, simple, light weight, and high-efficiency capability. There are still lots of scope to improve the performance characteristic of the MILO. Different aspects in which the improvements of the MILO device are required include mode control, power improvement, efficiency enhancement, and prevention of pulse shortening. This has motivated the author to take up the electromagnetic wave and electron beam interaction study, design, simulation, optimization and experimental testing in the present thesis. Accordingly, the work embodied in this thesis is divided into the seven chapters, as follows.

First chapter, 'Introduction and Literature Review' an overall view of the research topic has been provided. In Chapter 1, an exhaustive literature survey and state-of-the-art on various HPM sources, like, MILO, Reltron Vircator, Relativistic Magnetron etc., and their applications are narrated. After rigorously viewing both the version of relativistic conventional microwave tubes and special plasma vacuum devices, namely, MILO has been identified as an attractive HPM source for generating High Power Microwaves. Basic principle, working, advantages, and limitations of MILO has been briefly explained. The sub-assemblies and their functions of MILO have also been briefed in Chapter 1. The current research interest in the field of MILO is to enhance the beam power conversion efficiency and resolving the issues pulse shortening. The repetitive shots MILO can be achieved by improving the performance of cathode. The extraction of output power depends of the of the performance extractor cavity on the load side which are the other research topics of interest. In brief, Chapter 1 of the present thesis provides a bird-eye view of the background, application, basic principles, various components, and global scenario of the conventional devices are also discussed. At the end of Chapter 1, variants of the MILOs simulated and experimented for obtaining high power at different frequencies and comparison of MILO with the other HPM sources are presented in the tabular form.

In Chapter 2, the fundamental device operating principle and analytical approach of the crossed field devices based on classical approach and relativistic approach have been discussed. The particle motions in the MILO, linear magnetron and cylindrical magnetron have been explained. The fundamental mechanism of self-magnetic insulation and the condition for relativistic Brillouin flow have been described in detail by considering the process of explosive emission which is related to generation of plasma frequency in HPM sources. The variations of azimuthal magnetic field versus critical magnetic field are studied. The operating voltage and current for the designed parameters of MILO are discussed. The design methodology of MILO has been described through its analytical expression including charging current, critical current, para-potential current or total anode current, escapes current or spoke current and cathode design equations, etc. The oscillation condition for the cross field devices, such as, Hull cut-off, Buneman-Hartree and region of oscillation have been explained. Further, the beam-wave interaction mechanism in MILO has been understood through the magnetic cut-off, Diocotron principle, modes of oscillation. A detailed flow chart for the design of conventional MILO for the given specification has also been described.

In Chapter 3, the detailed design and simulation of an improved S-band conventional MILO have been described. The RF interaction structure of MILO as per the design was cold simulated in “CST Microwave Studio” to confirm the pi-mode frequency at fundamental mode TM_{01} mode. Further, to study the complete beam-wave interaction mechanism in MILO, this was modeled in "CST Particle Studio". The energy transfer phenomena and the spoke formation during the operation of MILO were studied. Further, by using the parametric optimization technique the power conversion efficiency of the MILO has been enhanced and the structural parameters including the length of the cathode and beam dump, inner radii of choke and SWS vane, and placement of stubs have been optimized. The reduction in cathode length could manifest several advantages: (i) additional electrons are available for interaction with the desired operating mode for enhanced efficiency (i.e., higher number of spoke electrons could participate in interaction), (ii) sufficient self magnetic field generation, and (iii) the reduced cathode length prevents cantilever axial shift and off-axis asymmetric emission of electron beam. The 3D PIC simulation predicted a peak RF output power of 6 GW at 3.1 GHz in the desired TM_{01} mode with a power conversion efficiency of ~25% for the diode voltage of 500 kV and current of 47.5kA. The present structural optimization significantly reduced the total length of the MILO by ~ 22% as compared to the earlier conventional MILOs. Further, to validate the efficacy the present simulated results were validated against the results available in the literature.

In Chapter 4, an Artificial Neural Network (ANN) based Particle Swarm Optimization (PSO) technique has been explored for MILO performance improvement through the optimization of structural parameters of the designed MILO structure. Different ANN based optimization techniques namely genetic algorithm, back-propagation, tabu search and simulated annealing and PSO algorithm are explored and described. The parameters control, flow chart and fitness function chosen for PSO are explained in detail.

This particular optimization technique has been preferred to achieve the maximum RF output power and power conversion efficiency in fundamental mode of operation of MILO. The effect of various parameters, including the inner radius of SWS vane (r_i), cathode radius (r_c), thickness of SWS vane (w) and circuit periodicity (s) have been studied by solving the fitness function using PSO technique. A S-band MILO design, as outlined in Chapter 3 has been chosen for the MILO device performance optimization purpose and the effect of these parameters on RF output power of MILO have been investigated using PSO. After optimization of structural parameters of RF interaction structure using PSO algorithm, the S-band MILO was simulated in "CST particle studio". The simualtion predicted an RF output power of ~ 7.2 GW at 3.1 GHz in fundamental TM_{01} mode with a power conversion efficiency of ~29%, while applying the beam voltage for 500 kV. The present simulation results of S-band MILO using PSO optimized parameters have been compared with the results obtained through parametric technique as discussed in Chapter 3. The efficiency of the device has been enhanced by ~4% through the PSO technique comparing with the parametric optimization technique. Because of optimization of design parameters using PSO, the total length of MILO device and the projection of cathode inside beam dump are reduced significantly. It was also observed from the literature that increasing the number of swarms more than 50 leads to degradation of the performance and the control parameters, namely, c_1, c_2 and w play vital role for the convergence of the algorithm and have to be chosen very optimistically. All optimizations on fitness function were carried out with the swarm size of 10. Yet, an improved performance can be obtained by using swarm size of greater than 10 but it would also increase number of fitness function evaluations. The comparison of simulated results for the optimized structural parameters of

S-band MILO using parametric technique and PSO algorithm has been presented. A MATLAB code has also been developed for solving the fitness function by linking it with the PSO algorithm.

In Chapter 5, the beam absent (cold) electromagnetic simulation of RF interaction structure of S-band MILO, has been carried out by reconfiguring the commercial PIC code "CST Microwave Studio". The operating π-mode frequency as per the design presented in Chapter 3 and validated for the dispersion characteristics obtained from the simulation and cold test measurements have been described. Based on the design and simulation, the assembly and piece parts drawings made using solid-works modeling software and the fabricated piece parts have using CNC lathe machine with high precision and accuracy have been discussed. Later, the piece parts assembled for microwave characterization using scalar network analyzer (SNA) based on resonant perturbation method has been presented. Comparing with the design π-mode frequency (3.3 GHz), the shift in cold simulated π-mode frequency due to the perturbation of electric field by the insertion of probes on both sides of the RF interaction structure has been explained. The deviation in measured π-mode frequency against the design and simulated π-mode frequency attributed mainly due to the fabricational tolerances along with perturbation of electric field caused by the insertion of the metallic perturbation probe. The measured values validated against the simulated results of designed operating π-mode frequency. The results obtained from both simulation and measurements have been found in close agreement within 3%, showing the efficacy of the device design methodology developed in this chapter. The complete MILO system along with the designed RF interaction structure was experimented as discussed in the next chapter.

In chapter 6, in order to study the concept of self-magnetic insulation of MILO, design and simulation of MITL carried out has been deliberated. Later, the fabricated structure of MITL using stainless steels and experiments carried out with the available pulse power supply (KALI-200) at MTRDC, DRDO, Bangalore has been studied. The concept of Self-magnetic field generation in MILO as per the design and simulation validated by the experiment has been explained. The piece parts and final assembly drawings of S-band MILO device made using solid-works modeling software have been presented. Detailed pulse power and RF power diagnostics have been explained. Further, the piece parts of S-band MILO as per the design and optimization as discussed in Chapter 3 have got fabricated at using CNC lathe and milling machine at MTRDC with high precision and accuracy. To radiate the RF power from MILO in TE_{11} mode, mode convertor called Vlasov antenna with perspex window designed, and simulated in CST studio. Later, the parts of Vlasov antenna and window have been fabricated using stainless steel material and perspex material, respectively. The S-band MILO device with Vlasov antenna has been integrated with the DC Pulse power supply of MTRDC and tested at the beam voltage of 485kV and current of 48.4kA in a single shot mode. The RF output power of 1.4MW has been obtained in the fundamental TM_{01} mode at the designed frequency of 3.26GHz. The positive point of our study is we have achieved magnetic insulation principle in the device as well as the device operation at the designed frequency and the mode. However, the radiated microwave power has been found much less than the designed device power. The reasons for not getting gigawatts of RF power as per device design have been found primarily due to the practical limitation in the RF diagnostics. The reasons and correction methods have been analytically and logically enumerated in this chapter. Efforts will be made in future to correct the RF diagnostics so that exact RF power output from the device could be measured.

7.1. Limitations of the Present Study and Scope for the Future Work

In the present thesis, performance study of S-band MILO for single shot operation has been carried out through design, optimization, development and experimental testing using high voltage and high current Marx generator at MTRDC, Bangalore. This MILO is tested for the beam voltage of 485kV and current of 48.4kA and obtained RF power of 1.4MW at fundamental mode frequency of 3.26GHz. However, the limitations of the work carried out and scope for the future work is presented below:

a) Since ground based and airborne applications demand RF power at multiple frequencies in single shot operation , more thrust has to be given for the design and development of Bi- / Tri- frequency MILO.

b) Till date MILO has been developed and experimentally tested up to PRF of 20Hz as reported in literature. For damaging / disrupting hardened electronics components in EMI and EMS environment, PRF (peak repetitive frequency) MILO has to be designed and developed 50Hz for repetitive shots operation.

c) In the present thesis, optimization of MILO using PSO has been carried out by varying one parameter and keeping other parameters of RF interaction structure are constant. It is suggested to vary all parameters simultaneously in PSO and to be check for higher power and efficiency.

d) The S-band MILO in thesis has been designed and developed for ground based applications and vulnerability studies on electronics components. The design and development of X or Ku band MILO has to be carried out for the airborne system applications.

e) Presently the S-band MILO is tested upto 485kV, 48.4kA and RF power of 1.4MW has been obtained at 3.26GHz. The beam voltage, current and frequency is closely matching with the design and simulation, but RF output power is low. For getting gigawatts of power as per the design and simulation as discussed in Chapter 3, the experiment has to carried out further by maintaining high vacuum around 10^{-6}-10^{-7} Torr inside the MILO device by using proper pumping systems and by use of alumina window in place of perspex window at the mouth of the antenna to avoid breakdown due to high electric field.

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