Equivalent Circuit Approach to the Beam-Wave Interaction Analysis of the Magnetically Insulated Line Oscillator

THESIS

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CHAPTER 7

SUMMARY AND CONCLUSION

7.1 Summary and Conclusion

7.2 Limitation of Present Work and Scope for Further Studies.

7.1 Summary and Conclusions

High power microwaves (HPM) has attracted lot of attention to the system designers and engineers due to its vast and newly emerging applications in the defense, plasma physics, industry, thermo-nuclear fusion etc. The HPM devices are based on microwave and referred as microwave-electron beam devices or microwave tubes. They are used as the sources and amplifiers in the microwave, millimeter wave and THz wave bands of the electromagnetic spectrum. HPM devices are also being use in Directed Energy Weapons (DEW). The conventional microwave tubes and semiconductor based sources and amplifiers cannot generate high power microwaves. In case of HPMs, various 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 the new direction. In these devices, high voltages are used to produce the relativistic electron beam and the electron energies are comparable or greater than the 510 keV (rest energy of an electron). MILO is one of the HPM source capable of generating self-azimuthal magnetic field. Operational mechanism of a compact MILO device is robust and operating region ranging from P-Band to K-Band. The prime application of MILO is concentrated for the defense and telecommunication. MILO is one of the most successful, widely used device of the HPM sources family. Nevertheless, lot of research related perplexing issues are still to tackle for the improvement of the device performance. There are still lots of scope to improve the performance characteristic of the MILO. In MILO, the aspects in which the improvements are required include mode control, power improvement, efficiency enhancement, and pulse shortening. These aspects attracted and motivate author of this thesis to analyze the RF interaction structure of MILO using equivalent circuit approach and thus optimize different structure and beam parameters. The research work has been organized into seven chapters. The studies carried out in the present thesis are summarized in this chapter. The conclusions of the work are described and findings are also discussed here.

First chapter is 'Introduction' in which an overall view of the research topic is provided. Chapter 1 describes the fundamental of HPM system, their schematic diagram, a brief working principle and applications. The historical development of MILO is given in detail and chronological progress is described in detail. In fact MILO is a high power microwave source which is working on the principle of magnetic insulation where relativistic voltage is applied to provide necessary current, hence called relativistic. Various groups are active for theoretical and experimental work on MILO. The current research interest in the field of MILO is to increase the power conversion efficiency and tackle the issues pertaining to the problems of pulse shortening. The output performance improvement is achieved by improving the performance of cathode. Output performance is the function of the performance of load side is the other research topics of interest. Brief description of MILO sub-assemblies has also been explored in Chapter 1. In brief, Chapter 1 of the thesis provides a bird-eye view of the background, application, basic principles, various components, and global scenario of the conventional as well as various variants of MILO are also presented.

In Chapter 2, theory of fundamental operation of the MILO has been presented. In order to generate gigawatt pulses, MILO need explosive emissive cathode. Condition for explosive emission in addition with process of magnetic insulation is also being described in this chapter. Equilibrium properties of relativistic electron flow alongwith the insulated sheath for cylindrical diode configuration of

MILO are discussed, too. Working mechanism of various types of current flow alongwith the interaction structure is discussed in detail. These currents play an important role during beam-wave interaction mechanism. On the basis of various existing electromagnetic equations and law of conservation of energy, taking into account various structure and beam parameters, Hull cutoff and Hartree conditions have been discussed. These conditions are limiting condition at which the oscillations start and beam interacts with the RF interaction structure. The field theory method has been described and effect of axial periodicity on coaxial waveguide structure is analyzed in this chapter.

Chapter 3 deal with the design procedure for typically selected improved MILO. PIC simulations, on CST-Particle studio computational platform, have been carried out for the MILO structure whose parameters are typically selected after validating the design. This code has been already reported to be validated by several authors for such electron beam device applications. The 3 D structure modeling of the MILO device is described. The MILO structure is first simulated for its electromagnetic behavior in absence of the electron beam (cold condition). Eigenmode solver has been used to identify the resonant frequencies of operating mode and RF electric & magnetic field pattern for the corresponding mode. The dispersion relation for the MILO has been plotted using this simulation process. The MILO oscillates at π-mode with good efficiency, hence this mode has been chosen as operating mode for the present study.

After the electromagnetic analysis the beam-wave interaction analysis has been carried out for the estimations of the RF output performance of the device in the presence of the electrons (hot condition). In order to carry out RF oscillation study inside MILO and electron beam - RF wave interaction, the resonant structure of the device have been excited using a 600 kV DC rectangular pulse signal. The radiated temporal RF output power of 4.4 GW operates at resonant frequency 1.76 GHz, corresponding to power conversion efficiency of 14.4%, where beam voltage is 600 kV and total current is 52 kA. The electron spokes formation has been also observed and energy exchange between electron beam and RF also explained nicely. Finally the simulated results have been compared with the other results available in published literatures.

Chapter 4 deals with the electromagnetic analysis of disc-loaded coaxial waveguide structure using equivalent circuit approach instead of modal matching technique. Equivalent circuit analytical approach is an alternative technique for analyzing the EM structure which is relatively less involved and cumbersome compared to the field analytical approach. In this approach, the actual structure is treated as a transmission line characterized by a set of four distributed line parameters. Considering current and voltage Telegraphist's equations, the transmission line parameters such as shunt capacitance per unit length, series inductance per unit length, phase velocity and the characteristics impedance are analyzed for the proposed structure. This technique yields same dispersion relation as resulted from the field matching technique. Effect of various structure parameters on transmission line parameters and variation of phase velocity with frequency is also discussed. Dispersion relation is used to plot the dispersion characteristics as well as study the role of structure parameters to control its shape.

Chapter 5 deals with RF analysis of disc loaded coaxial waveguide structure for beam present case taking into account equivalent circuit approach. Field expressions for different regions are written considering presence of space charge waves. This analysis is carried out to obtain the temporal growth rate, released RF energy, oscillation frequency and RF output power. For further rigorous and simplicity, here equivalent circuit approach is preferred. In order to predict the oscillation in MILO using equivalent circuit approach, dispersion relation having real and imaginary part is solved numerically for defined structure and beam parameters. For validation of our result of temporal growth rate, we find our result in agreement with reported result using field analysis case.

Chapter 6 deals with the performance improvement methods for MILO. PIC simulation described in Chapter 3 and analytical approach in chapter 5, have been used extensively further for the exploration of the different performance improvement techniques used for the MILO. The major problem encountered in MILO, is that its power conversion efficiencies are not very high. In MILO device, it is due to fact that a large fraction of the dc input current forms the load current. Various methods to improve the performance of MILO are: considering tapered cathode in place of constant radius cathode. Optimizing the extractor radius in terms of quality factor and reducing the length of cathode under the collector. Optimizing the load parameters by introducing foil inside beam dump disk and the last is to optimizing the length between the extractor cavity and stub. Considering these steps, proper resonance between RF and beam electrons occurs, results in maximizing efficiency.These changes also helps in reducing the overall length of device.

7.2 Limitation of present work and scope for further studies

The key operational parameters for a MILO are peak power, efficiency, pulse width or energy per pulse. Maximizing device RF power output and efficiency has been an active area of research taking into consideration various beam and structure parameters. The major problem encountered in MILO, is that its power conversion efficiencies are not very high. In MILO device, it is due to fact that a large fraction of the DC input current forms the load current. The load current generates the azimuthal magnetic field needed to guide the initially radial beam into an axial flow and has no contribution to RF power. To improve power conversion efficiency, proper resonance should occur between extractor gap and interaction structure. Thus, maximum coupling of RF takes place between extractor gap and coaxial transmission line, so that proper RF radiation occurs. In order to extract maximum RF power designing of stub should be improved. To improve pulse shortening problem and shot-to-shot reproducibility, cathode structure should be improved. In order to overcome this problem, Bi-frequency MILO should be studied. In future analysis and simulation study of Bi-frequency MILO must be done in order to improve performance of MILO and overcome the above said limitations. Equivalent circuit analysis developed here is for loss-free case, and it should be explored further considering ohmic and dielectric losses of the device structure, to yield more accurate results.