CHAPTER 6

SUMMARY, CONCLUSION AND FUTURE SCOPE

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6.1. Summary and Conclusion

Reltron is a narrowband megawatt (MW) HPM source which is compact and efficient. Reltron fulfils the vital requirements of a high-efficiency microwave source, such as, intense electron bunching; least energy spread and efficient RF extraction without breakdown. It is developed through the exploration of the split cavity oscillator (SCO) which is comparable to the klystron cavity in nature. Its operating principle is also similar to the klystron where the RF power is coupled out through a series of output cavities from the intense electron bunches. But, it is primarily distinct in two way: (i) the bunching process is different and, (ii) the intense electron bunches are reaccelerated to the higher energy by applying an additional DC potential. The external DC magnetic field is not required in the reltron and, the self-magnetic field developed in the RF interaction cavity is used to the focus the electrons in the longitudinal direction. Long pulses, upto microsecond duration can be generated, which enables it to radiate both high RF peak power as well as high RF energy per pulse. The other features of the tube include frequency tunable, power conditioning elements, intermediate energy storage and the pulse forming networks. These attractive features and capability of this HPM source has motivated to carry out further research on this device.

The motivation behind the present work and the outline of the research problem is describe in Chapter 1. The basic concept of the relativistic version of the conventional microwave tubes such as relativistic klystron, relativistic magnetron, and relativistic backward wave oscillator as well as specialized high power microwave sources such as virtual cathode oscillator, magnetically insulated line oscillator and reltron are outlined with their schematic diagram, operating principle and their present status. Reltron is described by briefing its classification, attractive features, and applications. In fact, reltron is a highly efficient and compact high power microwave source in which microwave generation takes place through the formation of the virtual cathodes. The operating mechanism of the device is similar to that of the klystron in which the electron is modulation, and the RF is extracted from the bunched electron beam, but the bunching process is different in which electrons are velocity modulated twice, and the bunched electron beam is reaccelerated by applying an extra DC potential. The historical development of the reltron is presented in the chronological order. Few research groups are actively involved in the developing, as well as analysing the reltron device, but due to strategic in nature limited literature is available on reltron. The current research interest in the field of reltron is to develop a detailed analysis of the device through various analytical and simulation studies so that researchers and developers can understand the device physics.

The principles of fundamental operation of the reltron are presented along with a brief description of its major subassembly in Chapter 2. The field emission of electrons from a cathode via explosive emission process is summarized. The modulation cavity of the device operates in TM_{01} mode while resonates in three different resonating modes, *i.e.*, 0, $\pi/2$ and π modes according to their electric field patterns and the $\pi/2$ mode is selected as the desired resonating mode. The concept of post-acceleration process and its impact on the device performance is explored. The device oscillation condition is demonstrated by representing the modulation cavity as an equivalent parallel *RLC* circuit where it is assumed that the equivalent series resistance per unit length is *R*, equivalent series inductance per unit length is *L*, and the equivalent shunt capacitance per unit length is *C*. The phase angle for sustained oscillation is found to lie in between $\pi/4$ to $3\pi/4$ with a peak saturation amplitude at $\pi/2$ which conclude that since, reltron operates in the $\pi/2$ mode, no field exists in the coupling cavity, and the electric fields in the main cavities are in the opposite polarity, giving a maximum field strength in the modulation cavity. Therefore, phase angle should be kept at $\pi/2$, so that maximum field strength can be obtained. The amplitude and phase of the induced gap voltage within the oscillation range is analysed, and the effect of nonlinear saturation coefficient on these parameters is also demonstrated. An analytical approach is developed to calculate the electronic efficiency of the reltron. The analytical device efficiency and RF output power are found as ~ 44% and 280 MW at 3 GHz frequency, respectively, with the typically selected beam parameters whereas the reported experimental device, yielded an RF output of 235 MW with ~ 37% efficiency. The previously reported experimental values are found to be in agreement with the present analytical results within ~ 7-10%.

In Chapter 3, an analytical representation of the start oscillation current of the device is described taking the current flowing in the first and second grid spacing into the consideration. To set up the oscillation in the modulation cavity the beam current should approach the start oscillation current. The device design methodology of reltron oscillator is deliberated in accordance with the various design constraints. The process of designing a reltron includes operating mode corresponding to the RF interaction structure, operating frequency, electron beam parameters and mode of extraction at the output cavity, etc. The operating mode of reltron is typically selected as TM_{01} and the RF cavity dimensions are mainly determined by the device oscillation frequency. The various steps involved in the design procedure are discussed with the help of a flowchart. The device design is validated, and the performance is evaluated using a commercial PIC code "CST Particle Studio". For the device simulation, first, the reltron device structure is modeled as per the property of the structure material, electrical and dimensional parameters. Then electromagnetic (EM) simulation of the modulation cavity is performed, in the absence of the electron beam, to ensure the resonating frequency and the EM field profile gets produced inside the structure of the device. In 0-mode, the electric fields in the main cavities as well as in the coupling cavity are found to be in the same direction, and it resonates at 2.57 GHz frequency. Under π-mode condition, it resonates at 2.96 GHz frequency, the electric fields in the main cavities are again found to be in the same phase, but the electric field in the coupling cavity is now in opposite phase to the main cavities. While in the π/2 mode condition, the modulation cavity has no electric field in the coupling cavity and in the main cavities the electric fields are found to be in opposite phase which resonates at 2.76 GHz. All the three modes of the modulation cavity get excited but, only π/2 mode grows because it's unstable and maximum RF energy transfer only through this mode. After that, the reltron structure is simulated in the presence of the electron beam (hot condition) to observe the electron beam and RF wave interaction process, and gives information about the oscillation frequency, RF output power and efficiency of the device. With the typically selected beam parameters: total beam voltage = 850 kV, cathode voltage = 100 kV, post-acceleration voltage = 750 kV and beam current = 750 A, the RF output power developed through the present simulation is ~ 225 MW, and the corresponding extraction efficiency is ~ 36% at 2.75 GHz frequency. The PIC simulation value obtained for the device efficiency is in agreement with the experimental results within ~ 5%.

Starting from the basic principles, electrons and the electromagnetic wave interaction process in the device is analyzed in Chapter 4 of this thesis. Extending the concept of split cavity oscillator (SCO), the electric field responsible for electron beam bunching process in the side-coupled modulation cavity is presented. The relativistic klystron analysis is used to obtain the beam modulation process in the reltron. Further, the analysis is extended to obtain the RF energy developed this device. To evaluate the overall device performance, analytical computation and simulation using PIC simulation code "CST Particle Studio" using explosive emission model is carried out. The anode-cathode gap and the post-acceleration gap are driven by 100 kV and 750 kV DC potentials, respectively with 1 nano-second rise time. The initial beam current applied to the cathode is set at 750 A. With these specifications, the beam present simulation is performed for 100 ns duration. The electron's kinetic energy distribution showed that after the oscillation is set up, in the first half cycle the electrons decelerate in the first grid spacing and accelerate in the second grid spacing and in the second half cycle, a reverse process takes place due to the Lorentz reversal force. This acceleration and deceleration processes give a continuous double velocity modulation resulting in the highly bunched beams coming out from the modulation cavity which has very large energy spread and is eliminated by the application of post-acceleration voltage in the device. For the selected beam parameters of experimental device with 100 kV cathode voltage, 750 kV post-acceleration voltage and 750 A beam current at 2.75 GHz frequency, the RF energy growth of the reltron oscillator is computed using analytical study for 2.75 GHz frequency is found to be ~ 24 Joule for 100 ns pulse duration, which gives a stable RF output in around 12 ns time duration while the RF energy obtained through PIC simulation is ~ 22.5 Joule for a pulse duration of 100 ns. The analytical and simulation results are predicted the RF output powers of ~ 240 MW with ~ 38% efficiency and ~ 225 MW with ~ 36% efficiency, respectively, for 100 ns pulse duration. With the parametric variation, the analytical study is provided the maximum RF output power of ~ 550 MW with ~ 70% and with PIC simulation ~ 510 MW RF output power with ~ 64% efficiency when the cathode voltage was set at 300 kV, post-acceleration voltage at 750 kV and beam current at 750 A. The obtained analytical and simulation results are found in agreement of ~ 6% with the previously reported experimental values for RF output power and efficiency of the device.

Chapter 5 deals with the analytical and simulation studies of the virtual cathode formation mechanism during the RF signal build-up process in the reltron device. The analytical study of the space charge limiting current, RF electric field in steady state condition and beam wave interaction mechanism during reltron operation are carried out. The space charge limiting current responsible for the virtual cathode formation is estimated by extending the approach used for the relativistic klystrons. Then, the RF electric field distribution under the steady state of this virtual cathode condition is obtained. The vircator analysis concept is used to demonstrate the virtual cathode formation in the different cavities section of the reltron device. The purpose of this study is to find the necessary conditions for the generation and propagation of the bunched intense relativistic electron beam. The main issue with an efficient propagation of intense relativistic electron beam is the creation of negative potential well (known as the virtual cathode) which generates due to the beam space charge. The analysis predicted that two stages of the virtual cathode is formed in reltron. In the first stage, only one virtual cathode is formed while in the second stage two virtual cathodes are formed simultaneously, and thereafter it alternates. The modulation cavity consists of three metal grids which is similar to the multistage vircator, however, the operating mechanism is somewhat different. The electron beam coming out from the annular cathode via explosive electron emission process is pre-modulated while passing the first grid and forms a periodic dispersion mechanism propagating through the second metal grid. The electrons crossing the third metal grid enter into the post-acceleration region maintaining the bunch-dispersion cycle unchanged. The beam wave interaction process takes place in the modulation cavity in which the electrons are modulated once in the first main cavity and again modulated in the second main cavity. This dual-stage modulation process creates intense electron bunches. Since the electrons carry the negative charge with them, so these propagating space charge give additional potential to the electron beam. As a result, the potential energy becomes much higher than the kinetic energy and a deep negative potential well is created and electron bunch stops propagating further. This results in the formation of the virtual cathode formation. The virtual cathode formation mechanism in the reltron is different from the vircator in which two stages of virtual cathodes are formed. In the first half cycle, two virtual cathodes are formed simultaneously, one after the first grid and second after the third grid. Then in the second half cycle, these two virtual cathodes disappear, and a new virtual cathode is formed after the second. At the grids, the velocity of the electrons is maximum, and it starts reducing as electrons propagate towards the virtual cathode. The space charge continues to grow after the formation of the virtual cathode, and at a higher level, it stops the electrons. As a result, the virtual cathode comes closer to the grid until the kinetic energy of the electrons become high enough to pass through the virtual cathode. In this situation, the virtual cathode is disturbed, and the electrons propagate towards the extraction cavity. Thereafter, the new virtual cathodes are formed again after the space charge potential is set up. The virtual cathode formation in the reltron is a periodic process in which single and double virtual cathodes are formed, alternately. This periodic virtual cathode formation process in the reltron sets up oscillation, thereby the RF radiation. The electrons reflect between the virtual cathode and physical cathode also support the RF radiation. It is not necessary that oscillation frequency of the device, virtual cathode, and reflecting electrons have the same frequency. However, for optimum interaction, all these three should be forced to oscillate at the same frequency.

In the last chapter, Chapter 6, the work embodied in the present thesis are summarised and the significant conclusions are drawn from the major findings. The limitations of the present study are discussed pointing out the scope for the future work.

6.2. Limitations of the Present Study and Future Scope

In the present thesis, the reltron oscillator has been studied through various analytical as well as simulation studies is rather primitive and needs further pursuance. The limitations of the work carried out here and the scope of its future extensions are as follows:

(1) A typical reltron utilize conducting grids for passage of electrons and to confine RF waves. The main disadvantage of grids is that they can melt after a few shots. Even the tungsten which has the highest melting point can survive up to thousands of shots only. This drawback does not allow for utilizing a reltron for repetitive operation. It is essential to extend the present work to remove the metal grids.

(2) Another disadvantage is that the device requires a relatively high operating voltage for operation. With high operating voltages, the device impedance becomes high and creates possibilities for impedance mismatch problem for the interfacing with other external devices and DC pulse power supply. The future work may lead to the reduction of the operating voltage.

(3) Further, in some cases when a higher output level is required, an additional external DC magnetic field is required which makes microwave source bulky and heavier in weight. The requirement of externally applied magnetic field should be avoided to keep the device compact and lightweight.

(4) The beam dump section is not clearly described in the literature should be taken care to improve the performance of the device.

(5) The present work is limited to the explosive emission condition and for short pulse duration. The work can be further extended for thermionic emission and long pulse operation of the device.