CHAPTER 1

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INTRODUCTION AND LITERATURE REVIEW

1.1. An Overview of the HPM Sources

In recent years, considerable research interest has been aroused for the high power microwave (HPM) sources in the microwave tube community. Nowadays, the HPM sources are frequently used in many existing applications as well as in the emerging areas of research and innovation. High power microwave includes the devices operating in the range of frequency between 1 to 100 GHz and able to produce a minimum RF power of 100 MW. HPM sources can generate both type of RF pulses: (i) high average RF pulsed power and (ii) high peak RF pulsed power. The characteristics of high average RF pulsed power are continuous beam, high repetition rate, and long pulse duration, while the characteristics of high peak RF pulsed power sources are single shot, low repetition rate, and short pulse duration [Benford *et at*. (2007), Gold and Nusinovich (1997)].

The development of modern tube technology has a strong synergetic relationship with its applications. These new technologies are continuously getting embedded for HPM device development, for both military as well as civilian applications. The research efforts in the field of HPM sources have generated a technology motivated attention towards the HPM directed energy weapon (DEW). The DEW attack can disturb the system in two ways: (i) Hard kill- In this case, the electronic devices and components are physically spoiled, and this is caused by the induction of high current through the HPM pulses into the electronic circuit. This results into the flashover of electronic and semiconductor components. (ii) Soft kill- In this case, the electronic devices and components are deactivated with a malfunction as a result. A soft kill distresses a digital circuit when the HPM pulses of same magnitude as operating voltage of the electronic or semiconductor components enter into the system [Taylor and Giri (1997), Möller (2012)].

In general, the RF power is coupled into an object depending on the area sensitive to radiation and the coupling cross section. For front door coupling, this is often the area of a slot or the aperture area of an antenna. If the frequency of the HPM pulse is within the bandwidth of the antenna, more energy is coupled in, but the effect falls off rapidly for other frequencies. For back door coupling, it is more complicated, and the cross section depends on both frequency and position. The optimal coupling frequency of an object is hardly ever known beforehand. There are two main approaches to use HPM: one is to use a narrow band source, where the radiated energy is concentrated in a small frequency band. Another one is to use a wide band source, where the energy is radiated over a large frequency band. The intense relativistic electron beam can be generated by very high voltages for the HPM sources. And if the velocity of the electron beam approaches the velocity of light, then the term relativistic is used. In this situation, the current density of the electron beam becomes significantly high and also contain the relativistic effects [Benford *et at.* (2007), Taylor and Giri (1997)].

The HPM sources can be grouped into three different categories. In the first category, the conventional microwave tubes (such as, klystron, magnetron, and backward wave oscillator, etc.) are transformed into their HPM sources (such as, relativistic klystron, relativistic magnetron, and relativistic backward wave oscillator, etc.) by improvising these devices for the relativistic beam voltage with high current values and using the relativistic effects accordingly. The second category includes the fast wave device driven by intense relativistic electron beam (IREB), such as, free electron laser (FEL) and IREB gyrotron. These sources operate in the millimeter and submillimeter wave range and are complex in nature. Fast wave HPM sources are kept out for the scope of the present study. The third category comprises of specialist / dedicated HPM sources, such as, virtual cathode oscillator (vircator), magnetically insulated line oscillator (MILO) and reltron, which basically depend on relativistic effects arising from the high beam currents and voltages.

1.1.1. Relativistic Klystron

The relativistic klystron is a popular HPM source based on the phenomena of electron's coherent transition radiation. It is widely used in the charge particle physics and RF linear accelerator (linacs) applications. A basic schematic of the relativistic klystron is shown in Fig. 1.1. Typically, a relativistic klystron consists of a cathode, two or more pillbox cavities alienated by the drift tubes, extraction waveguide, and RF output window. The microwave generation in the relativistic klystron takes place in the pillbox resonating cavities along the propagation of the electron beam at discrete locations. The drift tube between the resonating cavities is designed in such a way that the propagation of electromagnetic (EM) waves are cut-off between the resonant cavities. Since no EM wave coupling occurs in between the resonant cavities, the coupling follows only through the electron beam which propagates from one cavity to another. In some cases, external magnetic field is also needed to guide the electron beam. Since the RF power is a function of frequency, and it is obtained by the extraction cavity which must couple out most of the electron kinetic energy which is dependent on the transit time of the electrons. Due to this limitation, the desired RF phase in the interaction cavity has to be maintained in such a way that the transit angle should not exceed 180° degree. In the relativistic klystron, the high energy electrons and the relativistic effects change the modulation process as compared to the convention klystron. By using a single gap to extract the electron kinetic energy becomes very difficult and to avoid such problems multi-gap cavities are needed. The relativistic klystrons are widely used as high energy drivers for free electron lasers, directed energy weapons, colliders and accelerators [Benford *et al.* (2007)].

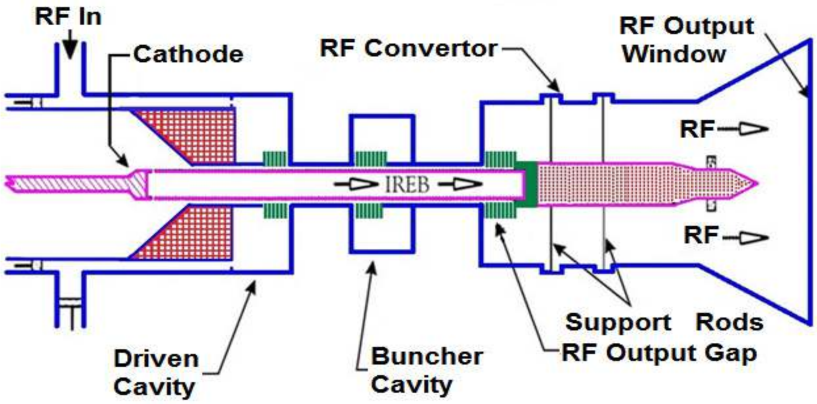

Figure 1.1: Schematic of a relativistic klystron [Gold and Nusinovich (1997)].

In early 1970's, Friedman developed a high power klystron driven by IREB at NRL. He demonstrated the modulation process of the IREB when it passes through a series of pillbox cavities connected with the drift tube and the method of extraction of the RF power. The experimental with an explosive emission cathode depicted an RF power of ~ 600 MW at ~ 2.9 GHz frequency with an efficiency of ~ 20% [Friedman (1975)]. Later, virtual cathode formation has also been demonstrated by the Friedman and co-workers. They developed a feedback mechanism like reflex klystron, and the device is termed as relativistic klystron oscillator [Friedman and Serlin (1985)]. To suppress the oscillations, the beam current was kept the threshold for the virtual cathode formation, and the first pillbox cavity was given an external RF signal which formed the relativistic klystron amplifier [Friedman *et al.* (1995)].

The relativistic klystrons can be categorized into three different types [Fazio *et al.* (1994)]. The first type, low-perveance relativistic klystrons with a solid beam was developed by Chodorow *et al.* at Stanford University in 1949 [Chodorow *et al.,* (1953)]. The second type was relativistic multi-beam klystrons are also designed at Stanford University. The device was a gigawatt power level of 10-beam in the L-band [Caryotakis (1998)]. At the Naval Research Laboratory (NRL), the third type of relativistic klystrons was designed. These are mildly relativistic tube with an annular beam operated with an explosive emission magnetically insulated diode, and coaxial cavities [Friedman, (1996)].

1.1.2. Relativistic Magnetron

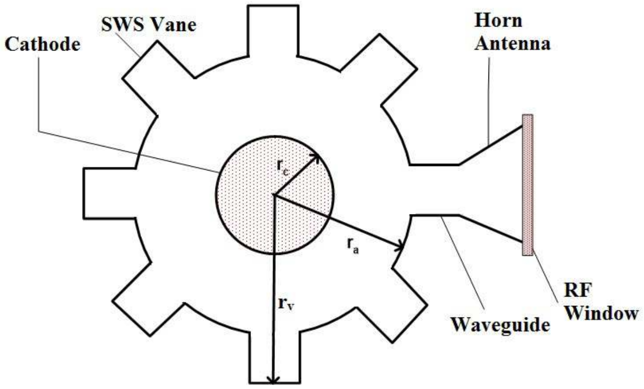

Figure 1.2: Schematic of a relativistic magnetron [Bekefi *et al*. (1976)].

The relativistic magnetron is the relativistic version of the conventional magnetron which is driven by DC pulsed power and cold cathode technology, and fundamental difference is that it uses high voltage and current. The cathode in the relativistic magnetron is surrounded by the anode cavity structure as shown in Fig. 1.2. The region between the anode-cathode (A-K) gap is the interaction region of the device, where the conversion of electric inputs to RF power takes place. The DC potential is applied between the anode-cathode gap, and an external DC magnetic field is applied in the axial direction. The suitable operating voltages and the fields can be determined from the mathematical relations known as Buneman-Hartree condition and the Hull cut-off condition. When these electrical parameters are applied to the properly designed relativistic magnetron, then electrons are emitted from the cathode surface and undergo the modulation process. Thereafter, the electron energy is converted into the RF energy and extracted out utilizing a loop through one of the cavities [Benford *et al.* (2007), Benford (2010)].

Initially, the relativistic magnetron experiment was demonstrated by Bekefi *et al.* in 1976 and they obtained an RF power of 1.7GW with an efficiency of 35% [Bekefi *et at.* (1976)]. Kovalev *et al.* developed a model of relativistic magnetron using diffraction coupling method, and this structure generated an RF of 4 GW at 9.2 GHz frequency [Kovalev *et al.* (1977)]. Adding the features of repetition rate mode operation and phase locking Benford *et al.* modified the relativistic klystron which provided a 6.9 GW RF power at the operating frequency of 4.5 GHz [Benford *et al.* (1985)]. Seven relativistic magnetrons were connected through the phase locking by Levine *et al.* and the device produced the RF power in the range 400-600 MW in the frequency range 1-3 GHz [Levine *et al.* (1991)]. Tunable relativistic magnetron was also carried out by Levine *et al.* and obtained 24% tuning from the centre frequency with 400 MW microwave power at 1.21 GHz and tuning range of 33% with 500 MW microwave power at 2.82 GHz [Levine *et al.* (1995)]. Fuks and Schamiloglu have extracted the RF power in the axial direction using a horn antenna and the relativistic magnetron provided 70% efficiency [Fuks and Schamiloglu (2010)].

1.1.3. Relativistic Backward Wave Oscillator

The relativistic backward wave oscillator (RBWO) is also one of the popular HPM sources. It is the relativistic version of the backward wave oscillator, an O-type and Cherenkov radiation based device, operating at higher current and voltage levels than its counterpart. The schematic diagram of RBWO is shown in Fig. 1.3. It consists of an annular cathode, reflector, slow wave structure (SWS), solenoid, output cavity and a beam dump. The RF interaction structure is a periodic rippled slow wave structure (SWS), and the annular cathode is kept closer to it. The external DC magnetic field is applied in the along the propagation of the electron beam. When the intense relativistic electron beam is injected into it, the slow space charge waves interact with the electron beam. After the beam wave interaction, the kinetic energy of the electron beam starts decaying which gives rise to the negative growth rate. The reflector plays a vital role in the RBWO operation as it transforms the backward reflected waves into the forward propagating waves. If this phenomenon does not occur, the reflected waves can reach and damage the cathode. The SWS structure is used to decrease the phase velocity of the RF wave in such a manner that the electron beam gets synchronised with it. The operation of RBWO lies in the region where the group velocity drops to negative and leads to the growth of the backward waves. As a result, the electrons are propagating in the reverse direction, and an internal feedback mechanism is provided. As soon as, the beam current exceeds the start oscillation current limit the devices oscillation starts and as the phase velocity of the electron beam becomes nearly equal to the drift velocity than the maximum RF wave interaction takes place. The RBWO is widely used to the high power microwave generation for the military applications [Benford *et al*. (2007), Swegle (1987), Levush *et al*. (1992)].

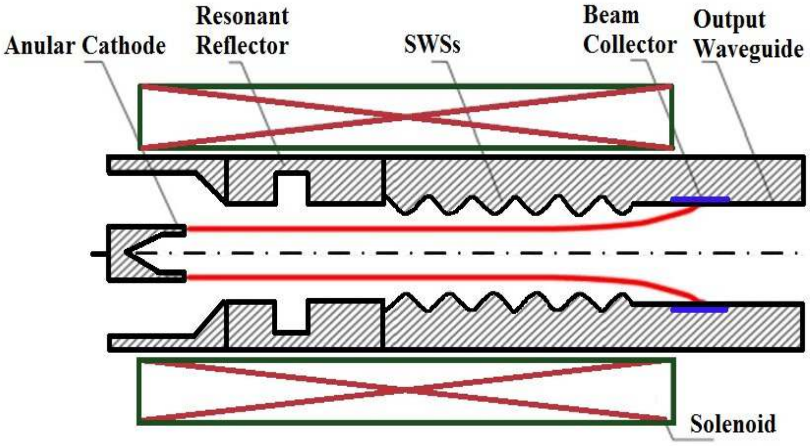

Figure 1.3: Schematic of relativistic backward wave oscillator.

The linear theory of the relativistic backward wave oscillator was provided by Swegle *et al*. and Levush *et al*. describing the basic theory of operation and beam wave interaction process [Swegle *et al*. (1985), Levush *et al*. (1992)]. The conventional RBWO with a cut-off neck reflector was demonstrated by Moreland *et al*. and by varying the length of smooth wall waveguide inserted either side of SWS ~ 5% frequency tuning range was obtained [Moreland *et al*. (1996)]. The modified structure of with the resonant reflector (RR) structure was proposed by Guinn *et al*. and the modified structure provides a pre-bunching of the electrons which improves the performance of the device in terms of RF output power and efficiency of the device [Guinn *et al*. (1998)]. The introduction of the non-uniform SWS along with the variable coupled impedance enhances the synchronism between RF waves and the decelerated electrons which result in the improved efficiency of the device up to 40% [Wen *et al*. (2000)]. To increase the velocity modulation, two uniform slow wave structures separated by a drift tube was attached [Zhang *et al*. (2004)]. Song *et al*. revealed a new type RBWO with two resonant reflectors separated by a finite gap as a consequence the electric field strength is distributed among the resonator reflectors and the pulse length of the RF signal is increased [Song *et al.* (2011)]. The trapezoidal resonant reflector was proposed by Cao *et al.* and this reflector shifts the electric field towards the centre of the resonant reflector instead of the edges as in case of the rectangular resonant reflector and the probability of RF breakdown [Cao *et al.* (2014)].

1.1.4. Virtual Cathode Oscillator

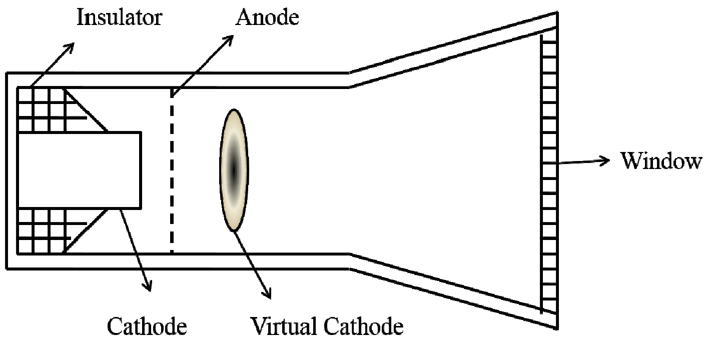

Figure 1.4: Basic configuration of virtual cathode oscillator.

Unlike the other HPM sources discussed earlier, the virtual cathode oscillator (vircator) has no conventional counterparts. It differs from the other HPM sources, the way it generates the RF radiation. The features of the vircator are its operating frequency which can vary 300 MHz to 40 GHz, no external magnetic is required, simple design and frequency tunability. The main drawback of the vircator is its low efficiency.

A basic virtual cathode oscillator configuration is shown in Fig. 1.4. It consists of a cathode, high voltage pulser, anode foil and RF window. In the vircator, a DC potential is applied at the cathode surface and the electron emitted through the explosive emission process. Due to this phenomenon, a plasma layer is formed on the surface of the cathode. This plasma layer helps in the passage of the high current density electrons, and these electrons are accelerated towards the anode foil. The anode foil is transparent in nature and allows electrons to propagate through it. Therefore, the accelerated electrons are injected into the cylindrical drift tube. The mechanism behind the operation of the virtual cathode oscillator is that the electron beam can carry the current up to a certain limit. And when this threshold point is exceeded, the potential energy of the beam becomes a significant fraction of the kinetic energy of the beam. In this situation, the beam current approaches a critical current known termed as space charge limiting current. As a result, the electron beam is unable to propagate forward and creates a negative potential well known as the virtual cathode. After the virtual cathode formation, some of the electrons having sufficient kinetic energy to cross the virtual cathode while the remaining electrons oscillate in between the physical cathode and the virtual cathode and this lead to the growth of the electromagnetic waves in the virtual cathode oscillator. The operating mode of virtual cathode oscillator is TM mode and therefore, mode conversion becomes a necessary part for RF extraction [Benford *et al.* (2007), Granatstein and Alexeff (1987)].

High voltage and current are required for the vircators, and device performance is very much dependent on the cathode material. The electrons are emitted through the explosive field emission through the dielectric material, such as, velvet whereas in the carbon fiber cathode materials, the electrons are emitted from the plasma layer formed on the cathode surface [Adler *et al.* (1985), Miller (1998), Shiffler *et al.* (2001)]. The vacuum quality inside the device gets lowered down due to the generation of the high plasma layer which also degrades the performance of the vircator. To avoid this discrepancy, the conducting emitter materials, such as, carbon velvet are used in which the emission process is carried out through field emission [Garate *et al.* (1995), Shiffler *et al.* (2002), Roy *et al.* (2009)]. To improve performance of the vircator, the multistage axial vircator has been developed [Champeaux *et al.* (2015)].

1.1.5. Magnetically Insulated Line Oscillator

The magnetically insulated line oscillator (MILO) is a crossed-field high power microwave source whose operation is similar to the magnetron. It syndicates the principle of magnetically insulated electron flow and slow-wave devices. MILO consists of a coaxial loaded metal discs working as the slow wave structure (SWS), explosive emission cathode, metal discs acting as a filter cum choke cavity, extractor cavity, inductive stub and the collector as shown in Fig. 1.5. A high DC potential is applied between anode and cathode causes explosive emission and forms the plasma layer at the cathode surface. When the current at the load side (charging current) become equal to critical current, magnetic insulation takes place near SWS, and electron beam drifts parallel to the cathode surface. Beam wave interaction takes place near the SWS structure when drift velocity becomes equal to the phase velocity of the RF wave, and the energy is stored in the form of standing waves in the SWS cavities. The stored energy can be coupled out through extractor in TM_{01} mode [Benford *et al*. (2007), Clark *et al*. (1988), Lemke *et al*. (1997), Eastwood *et al*. (1998)].

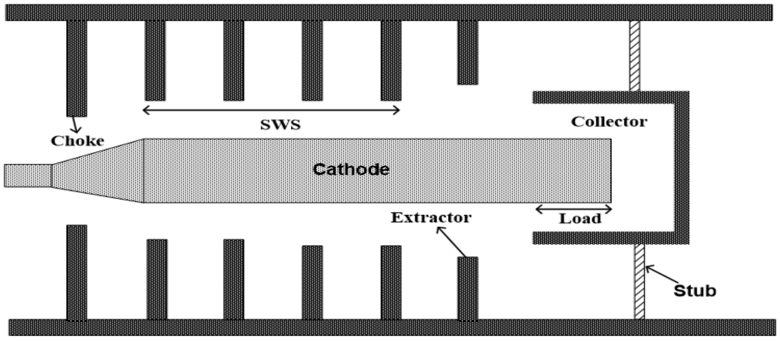

Figure 1.5: Schematic of MILO device.

Mendel *et al.* have explored the theory of magnetically insulated transmission line (MITL) and suggested the essence of magnetic insulation for the operation of large pulsed power system [Mendel *et al.* (1983)]. Clark *et al.* presented the concept of magnetically insulated line oscillator (MILO) similar to the linear magnetron and also investigated the preliminary experiment for the device in the US Air Force Weapons Laboratory [Clark *et al.* (1988)]. To extract the energy from cavities, initial simulation analysis was carried out by Marder using pseudo current algorithm [Marder (1989)]. The investigation and theoretical calculation of critical current, maximum efficiency and load length for Load-limited MILO with axial power extraction were carried out by Lemke *et al.* [Lemke *et al.* (1997)]. Haworth *et al.* investigated the effect of pulse-lengthening in MILO using different improvement in cathode section and choke insertion [Haworth *et al*. (2001)]. Eastwood *et al.* proposed a new MILO design using tapered slow-wave structures along with axial load current generation for magnetic insulation named it “Tapered MILO”. It amplifies the generated RF wave without the mode competition [Eastwood *et al*. (1998)]. Simulation and experimental investigation were carried out for the improved MILO with novel beam dump by Fan *et al.* With new beam dump design and one choke cavity section, the overall length of the conventional MILO has got reduced yielding the better efficiency [Fan *et al.* (2007)]. Chen *et al.* proposed the bifrequency MILO (BFMILO) and validated it through preliminary experiments [Chen *et al.* (2009)]. Dwivedi and Jain proposed the EM analysis in the TM_{01} mode of the disk loaded coaxial structure for MILO and the dispersion relation of the device were obtained [Dwivedi and Jain (2012)]. They optimized the dimensions of the S-band MILO using MAGIC PIC code for 600 kV, 35 kA and enhanced the RF power performance [Dwivedi and Jain (2013)]. Zhang *et al*. investigated a dual-band HPM source using MILO and Vircator in the same device with an overall efficiency of 13.4% in S and C-bands [Zhang *et al*. (2015)].

1.2. Reltron

Reltron is a member of the narrowband megawatt (MW) microwave sources that are efficient and compact which satisfies the essential requirements of a high-efficiency microwave tubes, such as, good electron bunching; a minimum relative energy spread of the electrons in the bunches and efficient energy extraction without RF breakdown [Miller *et al.* (1992)]. It grew out through the investigation of the klystron like split cavity oscillator (SCO). The basic schematic diagram is shown in Fig. 1.6. Its working principle is similar to klystron in that microwave power is extracted from a bunched beam using a set of output cavities; however; unique in two respect: the bunching mechanism is different from that in a klystron and the bunched beams are reaccelerated to higher energy to increase the energy with drawn in the output cavities. Unlike the klystron, the reltron does not require an external DC magnetic field to guide the electrons. Reltron can generate long RF pulses, up to microsecond duration, enabling them to radiate microwaves not only with high peak power, but also large energy per pulse [Benford *et al.* (2007)].

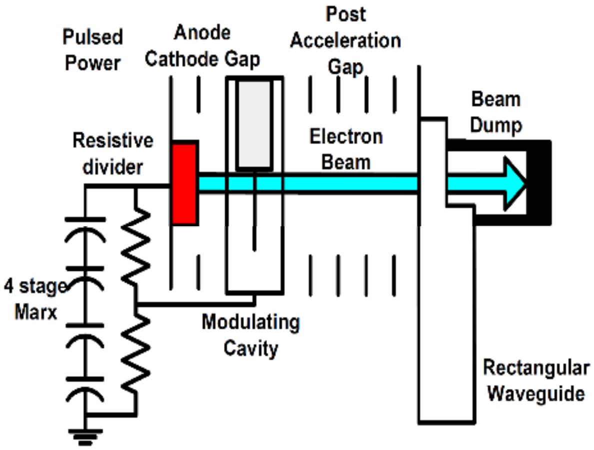

Figure 1.6: Schematic of the reltron [Soh *et al.* (2010)].

It is able to generate high power microwaves (HPM) with excellent power and frequency stability for the duration of the pulse. Reltron uses velvet cathodes which are cold cathodes that are readily available. Velvet cathodes are very cheap compared to thermionic cathodes and can generate current densities >1 kA/cm^2. The tube performance is independent of the load impedance [Miller *et al*. (1992)].

The first reltron is developed by Titan Advanced Innovative Technologies of Albuquerque in the year 1992 focused on compact, efficient and reliable HPM systems, and the advanced subsystems and components that enable the same. Specific subsystems of interest include pulse forming networks, intermediate energy storage, and power conditioning elements. These subsystems are designed for reduced size and weight while still meeting severe service, platform integration, lifetime and thermal management constraints [Miller *et al*. (1992)]. The advantages of reltron are that it can produce microwave pulse widths approaching 1 μs and pulse energies of a few 100 joules, outstripping the other HPM devices, like, relativistic magnetrons that are limited to pulse widths of about 100 cycles and pulse energies below 100 J. Apart from these, frequency tunable reltron can be tuned ±10% with respect to a central frequency [Gold and Nusinovich (1997)].

1.2.1. Classification of Reltron

Reltron can be broadly classified in the following two categories:

(i) *Gridded Reltron*: The gridded reltron uses grids in the modulating and the extraction cavities. Explosive emission cathode is used from a planar field cathode to emit the high current density electrons and no external DC magnetic field is used (the self-magnetic field focuses the electrons). This device is particularly suitable for high peak pulse power applications in the microwave frequency range.

(ii) *Gridless Reltron*: In gridless reltron, no grids are used in the device cavities. The electrons are emitted from a thermionic cathode and require a small external DC magnetic field to focus the electrons. This reltron is well suited for high average power applications requiring long lifetime or high duty.

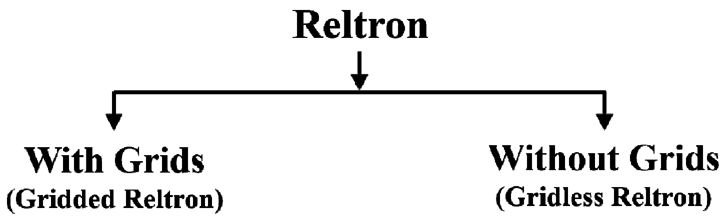

Figure 1.7: Classification of reltron.

1.2.2. Attractive Features

- High power, highly efficient, and compact high power microwave (HPM) source.
- External magnetic field is not required.
- No need of mode converter.
- Pulsed power in excess of 100ns duration.
- Frequency tuning is very easy with tuning plungers and idlers
- Efficiency of the device can reach upto 50%.

1.2.3. Applications

- Nonlethal HPM weapon.
- HPEM simulator.
- Electronic warfare.
- Directed energy weapon.
- Other possible applications in radar, imaging, material processing, and plasma science.

1.3. Literature Review

In 1992, Miller *et al.* at Titan Spectron, developed the first experimental version of the reltron. The initial 1 GHz reltron tube experiment was conducted with split cavity oscillator as a modulation cavity. With a total voltage of 800 kV and an average current of 1.2 kA, they were able to extract >400 MW RF power, with the extraction efficiency of $\geq 50\%$. The total RF energy of 84 J was obtained with 375 MW peak power. The 3-GHz reltron experiments were conducted using a Marx generator consisting of a series of two WR340 extraction waveguide with two output cavities with quality factor 20 for the first extractor and 40 for the second extractor have been selected. With initial beam current 750 A and total voltage 850 kV, they achieved a peak output power of 235 MW with extraction efficiency is nearly 40% [Miller *et al.* (1992)].

Miller *et al.* have presented an analytical model of rectangular output cavity to compute the dimension of different parts to optimize the RF extraction from the intense electron bunches. A frequency agile version of S-band reltron tube has been constructed by physically deforming the modulation cavity structure using plungers and tuning screws. When the frequency is tuned, the power dropped by approximately 3 dB at ±5% from the nominal center frequency of 3.04 GHz [Miller *et al.* (1994)].

Miller *et al.* have also developed 1 GHz reltron able to produce 600 MW RF power with 250 J per pulse and used a 3-GHz output extraction waveguide obtaining 45 MW peak RF power with 25 J per pulse. They also reported a 10 MW RF power with 35% efficiency with scaled down form of reltron was used with thyratron-switched transformer module at 25 Hz repetition rate [Miller *et al.* (1994)].

Miller *et al.* have also reported another reltron at an operating frequency of 1.25 GHz and having ~1.18-1.30 GHz tuning range. This HPM source provided 400 MW peak power at 1.23 GHz. The gridless reltron has been modeled and fabricated at an operating frequency of 2.856 GHz with the specifications 20 MW, 5μsec, 100 Hz for the typical parameters of 250 kV and 200 amperes of cathode potential and beam current, respectively, with the device efficiency of 40% [Miller *et al.* (1995)].

Miller has given a brief introduction of pulse shortening in reltron tube and surveyed the properties of the materials used for construction, vacuum pressure, fabrication methods and the conditioning process. To increase the energy per pulse, he used the conventional fabrication methods incorporating the thermionic cathode for electron emission, ceramic insulators, and brazed connexion capable operating at high-temperature [Miller (1996)]. Miller has mentioned several high voltage sources used to drive the reltron. Initially, it has been operated with Marx generator having a crowbar switch to accurately control the pulse width. For applications requiring repetition rates upto a few tens of Hertz PFN Marx pulsers have been used while the applications requiring repetition rate in excess of few tens of Hertz thyratron-switched, transformer-based systems were used [Miller (1997)].

Miller has fabricated the high peak power reltron with velvet cathodes, plastic insulator and O-ring seals using high-voltage pulsed power method for the repetitive pulse operation. This high power source emits electrons using explosive electron emission process, and the vacuum pressure plays a vital role in the tube performance. If the vacuum pressure reaches out the limit 10^{-4} torr, the source is unable to function correctly. He suggested CsI-coated graphite cathode as a potential HPM cathode material it generates less gas than the velvet [Miller (1997)].

Ding has given the analytical description of the RF generation process in the reltron and demonstrated the physical significance of the beam bunching in the side couple modulation cavity and the output waveguide [Ding (1997)].

Miller reported two major cause of pulse shortening in reltron tube: (i) high field stress in the cavities are caused by relatively good vacuum condition (10^{-5} torr) and (ii) when the vacuum pressure of tube upsurges into 10^{-4} torr range, the diode shortening occurring while performing the repetition pulse operation. He observed that the electric field stress should maintain below the threshold limit 150 kV/cm to avoid the pulse shortening phenomena in the side coupled modulating cavity [Miller (1998)].

Choi *et al.* have demonstrated the low operating voltage and compact HPM source reltron with its design and initial operating characteristics [Choi *et al.*(2001)]. Choi and Schamiloglu have presented a study on the pulse power system of the low operating voltage and compact HPM source reltron developed at UNM [Choi and Schamiloglu (2002)].

Kim *et al.* have performed the MAGIC3D simulation of gridless reltron using thermionic cathode. They performed the cold test simulation of gridless modulation cavity and obtained the $\pi/2$ mode at 2.887 GHz. With a 120 kV of initial DC beam potential, 800 kV of post-acceleration potential and 80 A of beam current, hot test simulations have been carried out with a 1.4 kG longitudinal external magnetic field. A total 38.3 MW of RF power has been developed with 52.7% efficiency [Kim *et al.* (2009)].

Soh *et al.* have given an analytical model to produce a maximum of 120 kV DC potential by utilizing double bipolar juncture 396 J Mark generator. The resultant DC pulse was approximately 1-4 μs with less than 0.25 μs rise time. The MAGIC simulation predicted an average peak current of 1.2 kA while the analysis provided a peak current of 1.38 kA [Soh *et al.* (2009)]. Soh *et al.* have also performed the circuit analysis of reltron side coupled modulating cavity. They have carried out MAGIC simulation of modulating cavity and obtained the $\pi/2$ and π modes at 2.70 GHz and 3.29 GHz, respectively [Soh *et al.* (2010)]. Further, Soh *et al.* have proposed a dual cavity reltron to upsurge the beam bunching permitting highly intense bunches to be formed [Soh *et al.* (2011)]. Soh *et al.* have developed a different type of reltron which uses multiple modes in place a single mode to enhance the RF power of the reltron. They designed an RF interaction cavity and an output waveguide that is cable of generating two modes simultaneously or separately. With 1 ns rise time step supple, the anode-cathode is driven by 175 kV while the post-acceleration region is driven by 500 kV. With TM_{01} mode excitation, they have generated 81 MW microwave power with 23% efficiency and with TM_{11} mode 74 MW power with 17% efficiency. By exciting both modes simultaneously, they were able to generate 128 MW microwave power with 35% efficiency [Soh *et al.* (2012)]. However, we have restricted our work for the single mode operation.

1.4. Motivation and Problem Definition

High power microwave (HPM) sources are required for various applications, such as, directed energy weapons, electronic warfare, EMP and HPEM simulators. Although we have various HPM sources in this category, but still there are ample scope to improve its efficiency, RF energy output and pulse width as well as it PRF. A relatively new HPM source: reltron, has motivated me due to its potential application in the military and as well as in the civilian applications. Reltron is a simple, compact and highly efficient HPM source and is in demand for the latest upcoming HPM applications.

We have presented a brief device description and operating principle of the reltron, then the concept of oscillation condition has been developed. An analytical model to calculate the electronic efficiency of the device has been demonstrated. A device design methodology of reltron has been presented and subsequently used to design the reltron. A reltron with an explosive emission model has been simulated using commercial 3D PIC code CST Particle Studio to validate the design constraints and to evaluate the device performance. The electron beam and electromagnetic wave interaction process is analyzed starting from the basic principles which include bunching mechanism, modulation process, and associated RF energy developed. The results obtained through analytical calculations are validated through PIC simulation of the device. A brief study of the virtual cathode formation mechanism is also presented to show the multistage virtual cathodes in the different sections of the cavity.

1.5. Plan and Scope

Reltron is one of the attractive alternatives for narrow-band HPM radiation sources when it comes to power per volume and power per mass. The maximum peak power reported from the experimental model is ~ 600 MW with ~ 50% efficiency. Due to its compact size and frequency tunability, it is a prominent device for HPM system applications.

In chapter 1, an overview of the high power microwave sources including the principle of operation and present status of the devices are described. Both the relativistic version of the conventional microwave tubes, such as, relativistic klystron, relativistic magnetron and relativistic backward wave oscillator and the new high power microwave sources, such as, virtual cathode oscillator, magnetically insulated line oscillator and reltron are presented. A detailed literature review of the reltron along with the motivation and problem definition are present. The plan and scope of the thesis is also illustrated.

In Chapter 2, following the previous studies author has presented a brief device description and the operating principle of the reltron which consists of a high voltage pulser, field emissive cathode, modulation cavity, post-acceleration gap, RF extraction cavity and a beam dump. Each sub-assembly is demonstrated along with their significance. The process of electrons emission from the velvet cathode via explosive emission is discussed. The operating mode of the modulating cavity and the three resonating modes *i.e.*, 0, $\pi/2$ and π modes are presented with pictorial view. The novel concept of post-acceleration introduced in the reltron is described, how it reduces the energy spread in the device and increases the beam power. The extraction of RF output power in TE mode without any mode converter is also presented. The relationship between the induced gap voltage in the first grid spacing and the return current due to the formation of the virtual cathode in the second grid spacing is demonstrated with the help of equivalent circuit approach. A mathematical model for the sustained oscillation condition is described to obtain the self-oscillation condition of the device as well as oscillation range. The electronic efficiency of the reltron is obtained by taking the ratio of the average kinetic energy (converted into the RF energy) to the initial electron beam energy. Kinetic energies are calculated by numerically integrating the relativistic electron motion expressions.

In chapter 3, the minimum current required to start the oscillation in the reltron known as the start oscillation condition is demonstrated analytically. A reltron device is designed 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 in detail. CST Eigenmode Solver is used for beam absent simulation to study the electromagnetic behavior of the modulation cavity and the electric field patterns of the three modes are depicted with their resonating frequency. A reltron with an explosive emission model has been simulated using commercial 3D PIC code CST Particle Studio to validate the design constraints and to evaluate the device performance. The electron beam bunching during the RF interaction process is presented explaining the phenomenon of the double velocity modulation. The effect of cathode voltage and the post-acceleration voltage on the performance of the device is also explored.

In Chapter 4, a beam wave interaction process in the reltron device is analyzed starting from the basic principles. The electric field responsible for electron beam bunching process in the side-coupled modulating cavity is presented. The metal grids in the modulation cavity allow the electrons to pass through and confine the RF waves in between. Due to the reflections of the RF wave from the metal grids, only standing waves exist in between the metal grids and therefore, the axial electric field is expressed as the combination of the standing waves and the space-charge waves generated inside the cavity. The process of the transformation of the electron beam velocity modulation into the density modulation in the modulation cavity is presented. The influence of deceleration/ acceleration potential on the electron bunching is also incorporated. For an optimum electron beam and RF wave interaction in reltron, the space charge waves are synchronized with the electron beam and using the law of conservation of energy, the RF energy developed in the device is calculated analytically. Further, to validate the analytical calculations, the reltron device is simulated using PIC simulation code "CST Particle Studio" for the typically selected beam parameters.

In Chapter 5, a study of the virtual cathode formation mechanism is demonstrated using analytical as well as simulation studies. The IREB currents lie close to the space charge limiting current and the self-magnetic field developed in the device is sufficiently high to propagate the electrons only in the longitudinal direction. The analytical description of the space charge limiting current is presented along with the steady state virtual cathode condition. The virtual cathodes are formed due to the potential depression of electrons, in which some of the electrons are reflected back towards the real cathode, and due to the cathode potential, they have reflected again towards the virtual cathode. These reflected electrons also take part in the modulation process. The multistage virtual cathode formation in the reltron is demonstrated. The condition of single virtual cathode and multiple virtual cathode are studied through both analytical as well simulation approach.

In chapter 6, the research work presented in the thesis is summarized. The conclusions of the work are described, highlighting the major findings and their significance. Future scope and extension work is outlined.