CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.0 Introduction

The application horizon of microwave based devices is ever expanding in diverse fields like defense, telecommunication, navigation etc. Microwave devices have played an important role in a variety of fields which includes accelerators, magnetic confinement fusion, communication, earth and space observations and military applications. Military use of microwave devices covers radar, communication, electronic warfare, electronic counter measures and testing. Recently, efforts have been made to develop techniques to generate high-power microwave and analysis its linear and nonlinear propagation through dielectric media. A whole new branch of physics evolves to explore the high-power microwave (HPM) devices. Broadly, HPM includes analysis of microwave and millimeter waves which frequencies lies in the range of 1-100 GHz and having peak power >100MW. In general, these waves are considered to be either pulse of long duration with high pulse repetition frequency (PRF), or continuous wave. Additionally, the high peak power, pulse of short duration and low PRF is also considered for HPM. HPM devices are proposed to be use in variety of civilian and defense applications.

1.1 Overview of HPM

The perspective of microwave based devices is broad and highly applicative. It continues to expand even with competitive incursion from solid-state devices. Integration of ever advanced technology results extensive applications of microwave tubes in the high power, high frequency regime. The main function of high power microwave devices is to generate and amplify millimetre waves. The prime applications are in communication, radar, electronic warfare, missile tracking and guidance, remote sensing, directed energy weaponry (DEW) using HPM. Further industrial heating, cooking, material processing, hyperthermia, plasma heating for controlled thermonuclear energy research, atmospheric purification of Freon's, Ozone generation, advanced electron accelerators in high energy physics research, satellite power station, and so on [Andronov *et al*. (1968), Benford *et al.* (1998)]. HPM sources are garnering interest around the world, due to their reliable applications for defence and military purposes [Barker *et al.* (2001), Schamiloglu (2004)]. In addition to the aforementioned applications, considering the principle that the absorption of a material increases with frequency, the high power microwave devices are also being use for volumetric and selective heating. Due to the high heating rate HPM may also be used to develop fine and ultra-uniform grained ceramics. Such ceramics are reported to be quite strong and less brittle in nature. These new ceramic composite materials retain their high strength under high temperature and corrosive conditions. HPM help to produce light weight ceramic engines for aircraft and automobiles, additionally, strong and long-lived ceramic walls for thermonuclear power reactors [Gaponov-Grekhov *et al.* (1994), Grantstein *et al.* (1987)]. Considering the increasing attenuation coefficient of the atmosphere with frequency, High power microwave tubes will cater to the requirement of non-interfering high information density communication and provide high powers for millimetre-wave radars for their range and resolution. These devices are also in demand for the space-debris, phased-array mapping radar, ground probing radar, and for the detection of underground materials, like, the gun emplacements, bunkers, mines, geological strata, pipes, voids, etc. [Gaponov-Grekhov *et al.* (1994)]. HPMs found other potential applications in impulse radar for the range resolution as well as for the detection of stealth aircraft, etc. HPMs also contribute for environmental research by using cloud-radar which is believed that clouds can dominate the effect of greenhouse gases in global warming [Barker *et al.* (2004), Barker *et al.* (2001), Grantstein *et al.* (1987)].

Last two decades witnessed enormous growth of interest and research in the field of HPM technologies due to its vast applications in modern warfare technology. Use of conventional weapons does produce collateral and human damages along with long term radiation hazards. Henceforth, it is imperative to develop a new generation of electromagnetic non-lethal weapons like HPM devices. HPM weapons are designed to produce electromagnetic interference and/or damage with peak radiated power level of >100 MW or more, or pulse radiated energy of 1 Joule per pulse. The exploration of new and unique concepts for high power microwaves, millimeter waves and sub-millimeter waves has progressed rapidly in recent years. AHPM weapon is a "device designed to disrupt, degrade, or destroy targets without damaging infrastructure or hurting people by radiating electromagnetic energy in the RF spectrum, typically between 10 MHz and 100 GHz" [Robert J. Capozzella (2010)]. HPM weapons are used to disturb or destroy electronic equipments remotely by inducing high voltage and current. Now-a-days, research has been focused to develop efficient HPM sources, such as Backward Wave Oscillator (BWO), Magnetron, Magnetically Insulated Line Oscillator (MILO) and Reltron etc.

Scientific and engineering community further divides HPM sources into two categories namely narrow and ultra wide bands. A narrow-band device emits all its energy within one percent of the central frequency (10 – 100s of megahertz depending on the frequency) whereas an ultra-wideband device disperses its energy over a bandwidth from 100s of megahertz to several gigahertz wide [Weise *et al.(*2005), Cecilia Möller(2011)].

A tentative mechanism of disruption or destruction of devices by Microwave is as follows: coupling of RF energy to a circuit produces stray currents and voltages, causing molecular heating. The exact effect depends on several factors including beam characteristics (range, frequency, power level, pulse width, etc.) and target composition pathways into an electronic system. First, RF energy enters in system through a component or sensor designed to receive the energy, like, a radar antenna, known as front-door coupling [Guoqi Ni *et al.* (2005)]. Second, RF energy may enter through other apertures or cracks that allow the energy to diffuse into the system, known as back-door coupling. Any electrically conductive material may act like an antenna for HPMs. Once the stray currents and voltages enter the system, they disrupt or destroy the individual electronic components [Forster (1963)]. Ultra-wideband HPM is ideal due to wide range of wavelength providing multiple coupling mechanisms and points of entry. This is advantageous when the target composition is not known.

1.2 Working Mechanism of HPM system

HPM systems are based on HPM sources. A major research studies on HPM sources concentrate to address the problem of pulse shortening in narrow band HPM tubes. This problem limits the amount of energy in the radiated pulse due to processes that terminate the RF generation well before the pulsed power source turns off. Potential applications of HPM sources seek longer pulses (microseconds) at gigawatt range of RF power, thus pulse shortening in microwave tubes is a concern that has received a lot of attention during the designing of the high power source [Benford *et al.* (1998)]. A working mechanism of HPM system can be understood by the simple block diagram shown in Figure 1.1.

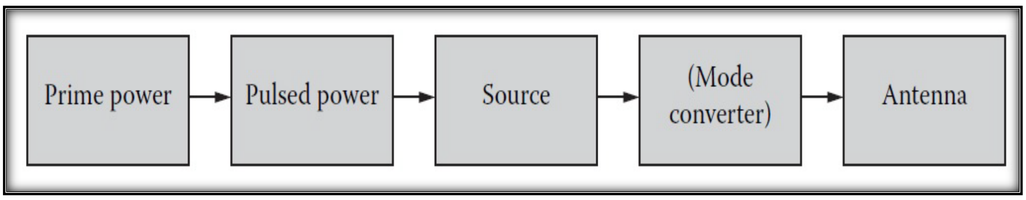

Figure 1.1: Primary components of HPM systems.

Initially, a power subsystem (e. g. Marx generator) generates relatively low power electrical signal either in form of a long pulse mode or in continuous mode. To produce short pulse width, fast-rising, low-impedance beam a pulse-forming line (PFL) is coupled to the Marx generator. PFL takes the low power/long-pulse electrical power, stores it and then switches it out in high power electrical pulses of much shorter duration. Pulse forming network provides transformation of heavy current to an impulse high voltage (hundreds of kV), which feeds a high power microwave electron tube (HPM ET). The generated microwave is emitted through antenna to the space. An antenna which directs the microwave electromagnetic output essentially compressing that output spatially into a tighter, higher intensity beam.

1.3 Overview and Classification of the Microwave Tubes

Based on the electron beam and RF wave interaction mechanism, microwave tubes can be classified in two groups: the ‘O’ type and ‘M’ type. In the O-type tubes, the electrons move in the longitudinal direction due to a longitudinal magnetic field and interact with the longitudinal electric field supported by the interaction structure. The interaction involves longitudinal space-charge wave and axial kinetic energy of the electron beam which finally convert into electromagnetic waves.

In M-type tubes, evolution of the electrons is performed in perpendicular DC electric and magnetic fields for the interaction with RF, and hence the device is also called as a crossed-field device. In this type, the transverse space-charge wave take part in the beam-wave interaction and the potential energy of the electron beam is converted into electromagnetic wave. For example, travelling-wave tube and klystron belong to the O-type, while magnetron and crossed-field amplifier (CFA) belong to the M-type electron beam devices.

The microwave devices can be further classified on the basis of phase velocity of the RF waves, as the slow- or fast-wave devices. For example, traveling-wave tubes and magnetrons utilize slow RF waves whereas gyrotrons employ fast RF waves for the interaction with the electron beam. The kinetic or potential energy conversion is also one of the criterions for the classification.

In another category, the microwave tubes can be classified as Cherenkov, transition, and bremsstrahlung radiation types [Bratman *et al.* (1987)]. In the Cherenkov radiation type, electrons move in a medium with a speed greater than the phase velocity of electromagnetic (EM) waves. CFA and TWT belong to this category. In case of transition radiation type, the electrons traverse along the boundary between two media of different refractive indices or pass through perturbations in a medium involving conducting grids and a gap between these conducting surfaces; example: klystron. In the bremsstrahlung radiation type, electrons emit radiation by moving with an acceleration or deceleration in electric and/or magnetic fields. The coherent waves are produced by electrons when the Doppler-shifted frequency of the EM wave coincides with the oscillation frequency of the electrons or with one of its harmonics [Bogdankevich *et al.* (1981)]. Gyrotrons, orotrons, peniotrons, and virtual cathode oscillators (VIRCATORs) are the examples of bremsstrahlung radiation type [Bratman *et al*. (1987)].

The multi-cavity klystron is a slow wave device, generally used as the power amplifier, which find applications in communication systems and accelerators. The klystrons operating in few hundreds of MHz to few GHz are commercially available for over 2 MW power CW and pulsed power over 200 MW with high gain and efficiency [Barker *et al*. (2001), Bers *et al*. (1986), Gilmour (1986)]. A variety of modifications of the conventional klystron have been proposed, e.g., sheet-beam klystrons and multibeam or cluster klystrons to cope with the limitations of rapid miniaturization of the interaction volume and the beam cross section with increasing frequency [Gold *et al.* (1997)]. The multi-megawatt, multi-beam klystrons have also been built to produce few tens of kilowatts to megawatts of power at hundreds of megahertz frequency for the linear accelerators and synchrotrons to be used for the study in high-energy physics [Chu (2004)].

The travelling-wave tube (TWT) amplifiers are also O-type of microwave tubes. TWTs can also provide power output ranging from a few watts to megawatts in microwave to millimetre wave frequency ranges [Gilmour (1986), James (1986)]. Helix and coupled-cavity interaction structures are most frequently used in the TWTs as its slow-wave circuit. The helix TWT has wideband potential as it is a 'non-resonant' behaviour while the coupled-cavity TWT has a limited bandwidth as it uses a stack of 'resonant' coupled cavities. However, the coupled-cavity TWTs have higher power capability than the helix TWTs. TWTs find their applications mainly in surface and airborne radars, as well as in high power, millimetre-wave communication systems [James (1986), Mendel (1973)].

Magnetrons and MILO are highly efficient oscillators belonging to the M-type. The magnetrons are extensively used in early radars, as pulsed power sources ranging from 0.5 GHz to 50 GHz operating frequencies with considerable power level up to 5GW [Benford *et al*. (1992), Gaponov-Grekhov *et al*. (1994), Florig (1988)]. The interaction structure of magnetrons are cylindrical, coaxial, inverted coaxial, and rising-sun versions [Carter (1990), Chatterjee (1999), Collin (1966), Gandhi (1981), Gilmour (1986), Liao (1988)]. The cross field amplifier (CFA) is another useful M-type device yielding efficient performance with low gain. The attractive features of CFAs involve low operating voltage, compact size, light weight, and moderate bandwidth which are suitable for airborne applications. Sometimes, CFAs are preferred to the TWTs in the final amplifier stage of a radar transmitter due to efficiency and weight considerations [Carter (1990), Chatterjee (1999), Collin (1966), Gandhi (1981), Gilmour (1986), Liao (1988)].

In the fast-wave electron beam device, like, gyrotron, electron beam is made periodic by introducing the gyration of electrons in a DC magnetic field. In an ubitron, the electrons are undulated with a wiggler magnetic field. Hence, microwave tubes can be classified based on the various aspects, however, it is difficult to make an explicit discrimination between these devices [Basu (1996)], such as, a transition radiation device like klystron may be looked upon as a Cherenkov device. Similarly, a bremsstrahlung device, like a slow wave cyclotron amplifier (SWCA), can be considered as a Cerenkov device [Basu (1996), Carter(1990), Chatterjee (1999),Collin (1966), Gandhi (1981), Gilmour (1986), Liao (1988), Gold *et al*. (1997)].

Since, present thesis is based on analysis of one of the slow wave devices; a detail discussion on slow wave devices can be found in following texts.

1.4 Slow Wave Devices

The most notable recent achievements which stand out are the ability to produce short-wavelength and long-wavelength radiation using electron beams and the ability to produce extremely high power. Devices, like, cyclotron resonant maser’s have generated coherent electromagnetic radiation at wavelength below 1 cm, and thus have filled spectral gap that existed between lasers at extremely short wavelengths and conventional microwave devices. At the longer wavelength in the microwave range, researchers working on high power devices, such as, the relativistic magnetrons, vircators, backward wave oscillator and Magnetically Insulated Line Oscillator (MILO), have generated short pulses with levels exceeding 1 GW. A specific interaction between an electromagnetic mode and an electron beam can be characterized by the efficiency, the frequency and a bandwidth. The interaction can result in a device that is ether an amplifier or oscillator. An important objective of current research is to study about the devices. For proper operation of a device require, proper electron beam, appropriate wave circuit, ability to couple the radiated output and beam collection. The formation of proper electron beam begins with power and power conditioning. A fundamental issue is the limit on beam voltage and current for pulse length ranging from tens of nanoseconds to steady state. This is an area in which the advent of Marx generator, pulsed power transmission lines, high voltage modulators has led to major advances for high power applications.

In slow wave devices, the synchronism is maintained by reducing phase velocity of the electromagnetic wave by means of the structure on the RF cavity walls or dielectric loading of waveguides. For slow wave devices, a slow wave RF structure is required where the phase velocity of radiation field is less than speed of light, to maintain synchronism between electrons and the electric field of the wave. Crossed field device, such as, magnetron employ a periodic RF structure built on the outer portion of coaxial configuration. The inner hub serves as a cathode, while RF structure acts as the anode.

1.4.1 Relativistic Magnetron

Magnetron is a cross field device, basically a diode, with a magnetic field parallel to its axis. The magnetron is the first truly practical microwave device. It provided the impetus for the development of microwave radar during World War II [Collins (1948), Liao (1995)]. The coupled cavities around the coaxial cathode in a magnetron support a number of potential operating modes. Each mode has its unique characteristics and field pattern. Mode competition in case of magnetron is an important issue because each mode grows from the ambient noise of the electron cloud in the Brillouin layer. The presence of many modes simultaneously leads the low power operation in the desired mode. Therefore, the key to high power is to operate in a single mode. Fortunately, relativistic magnetrons have less number of resonant cavities, usually 6 or 8, so the mode competition is less serious problem here. Modes are designated by a mode number *n*, which is the number of times the RF field pattern repeats in one rotation around the anode. In relativistic magnetrons, two principal modes are the π-mode, where the adjacent cavities are out of phase by π, and 2π-mode, where the each resonator has the same field pattern. The electric field structure of the π- and 2π-mode of an A6 relativistic magnetron is explained nicely by [Benford *et al.* (2006)].

The A6 relativistic magnetron is one of the most popular and reported in the literature. The resonant structure of this magnetron consists of six cavities with an azimuthal spacing of 60°. The radius of cathode is r_c and radius of anode is r_a. The radius of vane is r_v and angles subtended by cavity at the center is ψ. The cross sectional view of A6 relativistic magnetron is as shown in Figure 1.2.

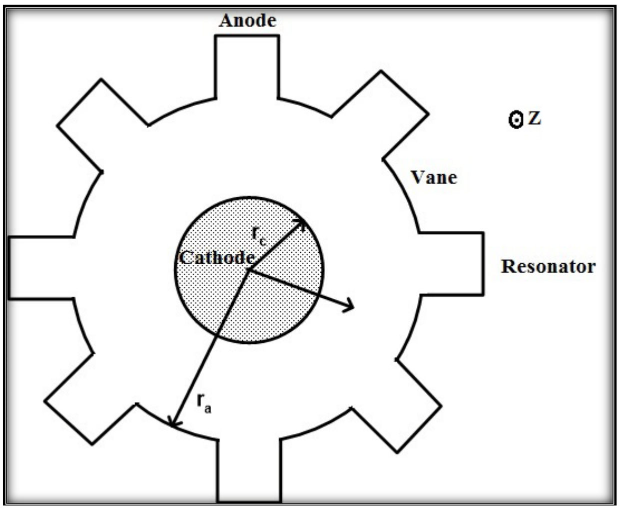

Figure 1.2: Cross-sectional view of the A6 relativistic magnetron.

The space between cathode and anode, where the interaction between electron beam and wave takes place is called interaction space. A DC accelerating voltage is applied between cathode and anode and the electrons are emitted from the cylindrical cathode surface due to the explosion of microprotrusions. If the field is sufficiently strong electron will be prevented from reaching the anode [Benford *et al.* (2006)].The electron cloud is referred as the Brillouin layer. Axial external magnetic field (B_Z)is gradually increased beyond B^*(at a constant voltage V) critical magnetic field, the space charge drift velocity will slow down. Strong oscillations in the mode will then cease [Benford *et al.* (2006)]. The magnetic field $B_Z = B_{BH}$ at which this happens is determined from the Buneman-Hartree condition. Buneman-Hartree voltage is the voltages at which oscillations should start provided at the same time magnetic field is sufficiently large so that undistorted space charge does not extend to the anode. Relativistic magnetron attractive features, like, capability of producing HPM with good efficiency and stability has led to a wide spectrum application, ranging from the human kind, industrial, defense, medical, etc.

1.4.2 Virtual Cathode Oscillator

Vircator (Virtual Cathode Oscillator) differs from the rest HPM devices in the way that microwave radiation is not generated from the interaction of an electron beam and a cavity. The anode of the vircator is transparent to electrons and the electron beam passes through it. The physics behind the vircator operation is that there is a limit to how much current an electron beam carries. If this limit is reached; the potential energy from the space charge in the electron beam is higher than the beam's kinetic energy and an electron cloud, a virtual cathode, is formed. A virtual cathode is formed when the magnitude of the beam current (I_b) of an electron beam injected into a drift tube exceeds the space- charge limiting current (I_{SCL}).

A single vircator is tunable for a frequency range (10 GHz-100 GHz). Since, vircator function above space-charge limiting current for the electron beam, given efficient operation it should be capable of much higher power than other microwave sources. These devices are capable of producing microwaves at levels above 1 GW for short duration, less than a micro-second. Vircators are HPM sources based on the bremsstrahlung radiation of relativistic electrons oscillating in electrostatic fields and are popular due to their simplicity and the fact that no external DC magnetic field is required for their operation. The virtual cathode is formed by exceeding the space charge limiting current, resulting in a depressed electrostatic field which is large enough to overcome the kinetic energy of incoming electrons. The electrons decelerate giving up energy to the microwave field. Then the electrons are accelerated away from the virtual cathode back toward the anode and toward the real cathode in a process called reflexing. This reflexing continues and produces microwaves at a frequency proportional to the square root of the applied potential and inversely proportional to the anode-cathode spacing. The schematics of Vircators are shown in Figure 1.3 for axial and radial extraction of RF power.

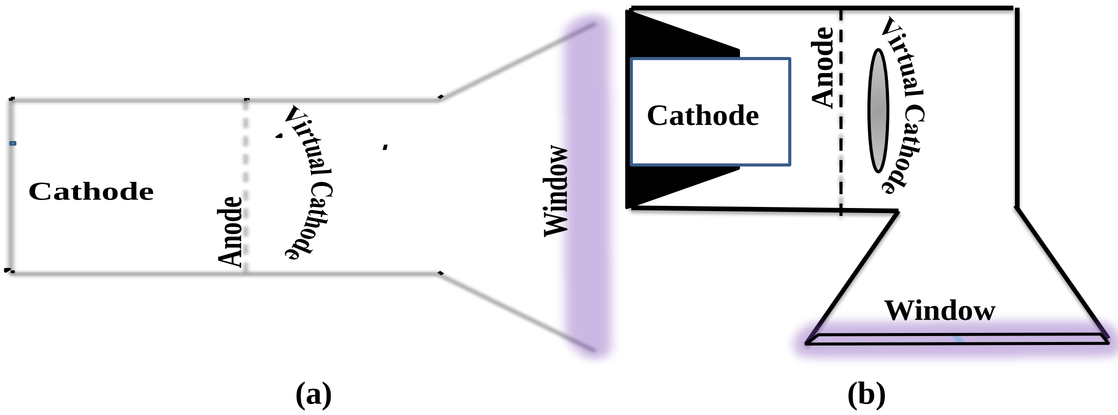

Figure 1.3: Schematic of Virtual Cathode Oscillators.

1.4.3 RELTRON

Reltron is also relatively a new type of high power microwave (HPM) source capable of generating gigawatt level power at the microwave frequency range[Mahto and Jain (2016)]. Its working mechanism is similar to klystron with some differences that it modulates the electrons beam twice in modulating cavity and then post accelerate the bunches toward the extraction cavity with relativistic energy without using external magnetic field [Benford *et al.* (2006)]. This device also meets the necessary conditions required for an efficient HPM source, such as, highly bunched electron beam; less electron energy spread and efficient energy extraction without RF breakdown [Mahto and Jain (2016)]. Post-acceleration and the multi-cavity output sections are the vital subassemblies of the reltron. The operating mode of device is TM_{01}. This device has an additional advantage of the direct RF output extraction through a rectangular waveguide in its fundamental TE_{10} mode without mode convertor. A typical schematic of the reltron oscillator is shown in Figure 1.4, which consists of a high voltage pulser, field emissive cathode, modulating cavity, post-acceleration gap, RF extraction cavity and a beam dump. A high voltage pulser is

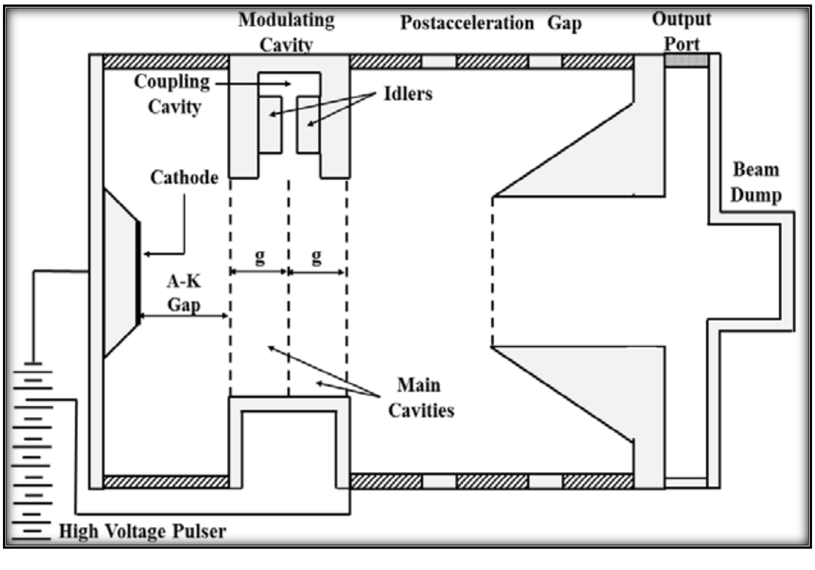

Figure 1.4: Schematic diagram of a Reltron [Mahto and Jain (2016)].

used to provide DC pulsed voltage to the field emissive cathode to produce very high density electrons under the explosive emission condition.

1.4.4 Magnetically Insulated Line Oscillator

Focused research has been done on microwave oscillators that do not require external DC magnetic field. Microwave oscillators that requires external magnetic field, employs two DC power sources for exhibiting magnetic insulation and also give rise to electrical breakdown as higher voltages are approached. These oscillators are having 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 oscillator that will operate at lower impedance and also eliminate the problem of voltage matching [Bekefi *et al.* (2006)]. To overcome the above problems, Magnetically Insulated Line Oscillator (MILO) has been used, which is efficient and compact high power microwave source. The main advantage of this device is that, it does not require any external magnetic field for magnetic insulation and it has very low impedance making it a suitable device to operate at higher power levels. To understand the working principle of MILO, it is necessary to understand basic physics behind self-insulating property of the relativistic electron flow which can significantly affect the microwave frequency and power level of the device.

Working mechanism of MILO is based on the relativistic flow of electrons in a coaxial magnetically insulated transmission line on which a slow wave structure, typically thin metal vanes, are loaded. Its geometry is similar to that of a linear magnetron or crossed-field amplifier. In the MILO, however, the magnetic field which insulates the diode is produced by the electron flow itself rather than being imposed by external coils. This eliminates the need to match the applied voltage to the magnetic field. Because both the insulating magnetic field and accelerating voltage are produced by the same source, the device can be run at high voltages without electrical breakdown. MILO is a slow-wave crossed field device, works on the principle of the self-magnetic insulation. Magnetic insulation is essential for the operation of large pulsed power systems. Insuring magnetic insulation in large pulsed power systems is necessary for transmission of pulse to load. Schematics of Load-Limited MILO is given in Fig. 1.5.

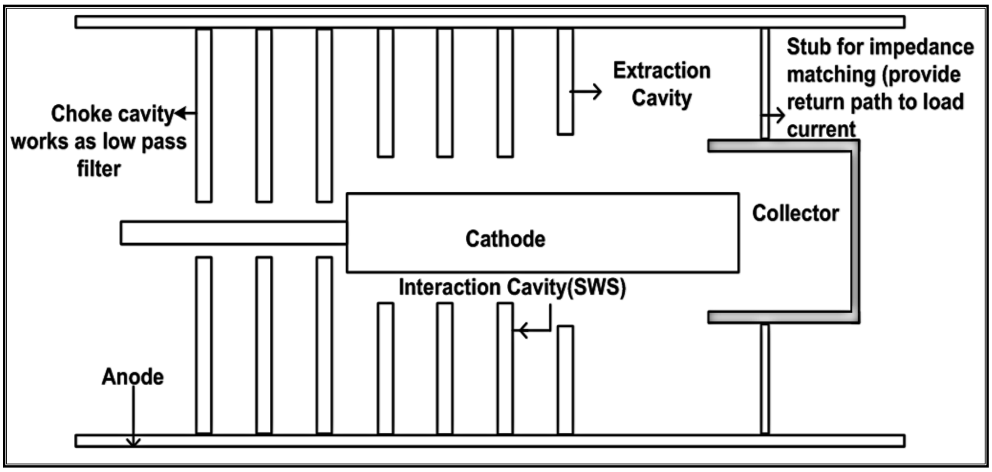

Figure 1.5: Schematic of Load-Limited MILO.

In MILO pulsed DC voltage is applied between anode and cathode. Anode is a slow wave structure comprising of the axially periodic metal discs which extend from a support surface of anode towards the cathode. Typically, MILO consists of a cylindrical field emissive cathode surrounded by a number of coaxial metal discs as the slow wave RF interaction structure, few additional discs forming the filter cavities towards input side that acts as the in-phase reflector enhancing the beam-wave interaction and reducing the load on the DC pulse power source. The interaction cavities oscillate in its fundamental *TM* mode. At this mode, each cavity behaves as a quarter-wave oscillator shifted in phase by π from its adjacent cavity. Thus, RF interaction cavity oscillates at π mode, which is not propagating mode and makes it possible to store large electromagnetic energy. To extract this energy, it is necessary to couple cavities to the output coaxial transmission line. This coupling is carried out using extractor having lower cut-off frequency which fixes the opening by which RF power is extracted converting standing wave into travelling wave and is propagated outside. Microwaves are generated by the interaction of TEM waves in the SWS with the space charge flows. Interaction is strongest when the wave phase velocity is approximately equal to the charge drift velocity and the charge flows fill the space between the anode and cathode to produce intense electron bunching and robust microwave radiation. RF energy is released by the interaction of electrons flowing parallel to the cathode with the EM field propagating through the SWS.

1.4.4.a Brief Description of MILO sub-assemblies

The major sub-assemblies of a MILO are (i) Cathode (ii) Choke cavity (iii) RF interaction structure (iv) Extractor cavity (v) Beam Dump.

(i) ***Cathode:*** It is an important sub-assembly that provides suitable electron beam for the interaction with the RF waves. In MILO high voltage DC pulse is applied between cathode and anode which causes electrons emission from the cylindrical cathode surface. The electrons are field emitted from the cold cathode by a specific process termed as explosive electron emission. The cylindrical cathode surface of the device is conventionally covered with the velvet where their microprotrusions act as the field emitters. The electric field present on the top of the microprotrusions leads to the appearance of a large surface charge density and consequently to a significant enhancement (up to 10^4 times) of the local electric field. The enhanced electric field causes intense electron emission upto the current densities $10^6 – 10^7$ A/cm^2. This leads to a fast increase in temperature of the individual emitters due to Joule heating, which transforms the field emission into the thermionic emission. Further, because of the extremely high current density, explosion from the top of microprotrusions takes place. This vapor state quickly ionizes and creates plasma flares close to the microprotrusions [Miller (1998)]. The individual flare quickly expands and combines with other flares that rapidly cover the entire cathode surface. This plasma cloud near the cathode surface can then be considered as an electron source with zero work function and accelerate electrons radially towards the slow wave structure. The experimental results show that the graphite cathode is superior to the velvet cathode in the lifetime and the shot-to-shot reproducibility during the repetitive rate operation, and it is a promising cathode for the MILO device under the repetitive rate conditions.

(ii) ***Choke cavity*****:** Typically, MILO consists of a cylindrical field emissive cathode surrounded by few metal coaxial discs forming the filter cavities towards input side that acts as the in-phase reflector enhancing the beam-wave interaction and reducing the load on the DC pulse power source. To prevent propagation of reflected wave, designing of choke radius should be at high cut-off frequency than cut-off frequency of RF interaction cavity radius. During designing the impedance difference between the last choke vane and the first primary SWS vane causes the electron flow closer to cavity openings where RF voltage is strongest, which helps in increasing the conversion efficiency.

(iii) ***RF Interaction Structure*****:** MILO consists of a number of metal coaxial discs as the slow wave RF interaction structure. One period of disc forms a cavity. The interaction cavities oscillate in its fundamental *TM* mode. At this mode each cavity behaves as a quarter-wave oscillator shifted in phase by π from its adjacent cavity.

Thus, RF interaction cavity oscillates at π mode, which is not propagating mode and makes it possible to store large electromagnetic energy.

(iv) ***Extractor Cavity*****:** The extractor part includes last MILO vane (called extractor vane) and the axial distance from the extractor vane and the coaxial transmission line (called the extractor gap). The inner radius of the extractor vane is slightly larger than the rest of the vanes to provide a good match of the extractor gap electric field to that of the output coaxial transmission line (CTL). Extractor converts standing wave into travelling wave which is to propagate outside.

(v)***Beam-Dump/Collector*****:** Radius of extractor vane is equal to the outer radius of beam dump for an efficient impedance match of extractor gap to output coaxial transmission line. Thus to extract RF energy, it is necessary to couple the extractor cavity with the output waveguide. Radius of extractor cavity is same as outer radius of beam dump, but larger than interaction cavities, since the radial component of RF electric field is maximum on the inner radius of extractor vane. This amount of radial component on vane tip is coupled directly to the output coaxial transmission line. The covering of collector on cathode constitutes an additional cavity which stores the RF energy generated in the MILO, and then transfers this energy to the external load in the form of pulse.

1.5 Literature review on MILO

In 1979 and 1983, Mendel *et al.* explores the theory of magnetically insulated transmission line (MITL), essential for the operation of large pulsed power systems. They reported that in the absence of magnetic insulation electrons will quickly short the system if explosive emission occurs from the surface that is subjected to electric field greater than 20-50 MV/m. In 1988, M. Collins Clark *et al.* reported paper entitled “Magnetically Insulated Line Oscillator” in which they illustrated simulated behavior of the MILO at 1.5GHz with efficiency ~10%. Different configurations of MILO geometries, such as, planar, coaxial and concentric were described in this paper. They also perform experiment at Sandia National Laboratories using 400 kV, 50 kA and 50 ns pulse generator and employing planar geometry of 15 cavities. Further in 1987, theoretical analysis of MILO was reported by R.W. Lemke and M.C. Clark using coupled Maxwell’s fluid equations approach. In order to validate their analytical results, they used PIC code CCUBE, for non-optimized geometry operating at 3.6 GHz with 5% efficiency. In1988, a U. S. Patent on the magnetically insulated line oscillator is taken by Larry D. Bacon, William P. Ballard, M. Collins Clarks, Barry M. Marder. Further to investigate about device parameters and how to extract power from the cavities, simulation analysis was carried out in 1988 by B.M. Marder using pseudo current algorithm. He concluded that the main parameters characterizing MILO are: anode-cathode gap, depth of cavities, periodic spacing of vanes, width of vanes and also compared simulations result with both linear theory and experimental data. Simulated MILO for 500 kV, 50 kA with 8 interaction cavities and achieved an overall efficiency of 10.9% with 2.1GW power at 50 ns.

In 1989, R.W. Lemke reported linear analysis of MILO, considering relativistic space charge flow. According to the theory given by Lemke, device oscillation frequency can be tuned by changing the beam energy (applied voltage), similar to the BWO. In 1990, Lemke *et al.*, reported experimental investigation of axial power extraction from a MITL oscillator. Ashby *et al.*, in 1995 have reported an experimental and simulation results of L-band MILO made of a number of simple axisymmetric discs at 1 GHz for 500 kV, 21 kA with efficiency of 10.8%.In order to investigate the physics of non-linear regime in a load-limited MILO, R. W. Lemke, S. E. Calico, M. Collins Clark, reported a MILO whose DC operating characteristics were determined by current-carrying load, thus load forms a part of a unique power extraction scheme. During their analysis it has been proposed that maximum power is obtained when an RF choke is used for the upstream boundary. Lemke also explained that maximum efficiency is accomplished by considering the spokes collectively as a modulated DC current crossing a voltage-modulated gap and derived condition for maximum power generation. Limitation of load-limited MILO is that most of the input power is being used to sustain the insulating magnetic field. This is the predominant source of inefficiency in a MILO. Lemke *et al.,* also reported efficiency enhanced load-limited MILO, that named after introduction of RF choke inside the structure. RF choke increases output power through two primary mechanisms: 1) by reflecting backward-propagating waves it contributes to maximizing feedback and 2) by increasing the downstream spoke current. The latter effect is due to the different impedances in the choke region and primary SWS region. When the emission region begins under the third choke vane, the impedance discontinuity between choke and primary SWS results in higher spoke current downstream, that is, the choke as we have implemented it is also a current launcher. Simulation for L-band MILO was performed using PIC code TWOQUICK for 493kV, 56.2kA, 3GW with efficiency of 10.8%. Finally Lemke *et al.,* in Air Force Research Laboratory/Phillips Laboratory, done experiment in order to validate analytical results for an MILO driven by a 500 kV, 60 kA electron beam, generated 1.5 GW pulses, but with significant RF pulse shortening. Because of significant RF pulse shortening observed in the load limited MILO, it was decided to build an all stainless steel, brazed version of the tube, known as HTMILO. This design was suggested by M. Haworth *et al.*, at the *IEEE* Int. Conf. Plasma Science, San Diego, in 1997. HTMILO tube is different with the load-limited MILO in two respects: extractor is supported by six quarter wavelength stubs rather than by four legs making gravity contact with the outer conducting wall. Secondly, changing constant radius cathode to the tapered cathode across launch point in the choke region allowed the HTMILO to increase its output power while tripling the pulse duration. During experiment carried by Haworth in 1998, (L-band, 500 kV, 60 kA, 3.2 GW) location between tapered cathode and choke vanes creates spurious electron emission. This results in design of improved HTMILO configuration. HTMILO consists of a velvet cathode energized by the 500 kV, 50 kA, 300 ns IMP pulser: a Marx-driven, coaxial-water-line machine. The RF circuit consists of four-cavity SWS designed for π mode operation at 1.2 GHz preceded by a two-cavity choke section that acts as an in-phase reflector and a coaxial extractor whose center conductor also serves as the beam load. Unfortunately, progress achieved in radiating higher peak power level in HPM source has been hampered by the pulse shortening problem. MILO has been taken into consideration by various researchers in order to improve phenomena of pulse shortening and shot-to-shot reproducibility.

Another main issue in the development of MILO is that it delivers poor efficiency. Maximizing power and efficiency has been an active area of research taking into consideration various beam and structure parameters. In 1998, experiment conducted by Haworth, led to the reliable results and helps in improving pulse-shortening problem. In addition, the microwave pulse has a 2.5 times longer duration than the tube of Calico *et al.* Problem facing by improved HTMILO configuration is its poor shot-to-shot reproducibility, due to cathode flare formation. To improve this problem, extractor side was also redesigned and simulated using 3-D PIC code QUICKSILVER, one change was to eliminate six $\lambda/4$ stub supports and replace them with three 1.27 cm outer diameter rods shorted at the outer conductor wall. Eastwood introduced tapered MILO design with novel tapered slow-wave structure, diode layout, and axial power extraction and predicts 20% efficiency during year 2000. The first was the cavity depth taper, which increases the group velocity of the slow-wave structure with axial position. The second was to place the diode into the slow-wave interaction space to allow further energy recovery from the diode current. The taper also leads to an increasing phase velocity, but the phase focusing and bunching mechanism in crossed-field flow keeps the electrons in synchronism with the wave to allow extra amplification of the RF signal. In 2000, Bao-Liang Qian *et al.,* reported on two-dimensional analysis of the relativistic parapotential electron flow in MILO where distribution expressions of the velocity, energy, density and self-electric and self-magnetic fields of electron flow were derived and analyzed numerically.

In 2001, in order to increase the frequency of MILO, concept of Vircator-MILO has been proposed, in order to improve the limitations of virtual cathode oscillator and MILO. During the same year, Yulin yang *et al.*, reported a novel method for increasing MILO frequency considering the design of a high power and high frequency MILO. In addition to the surface emission on the cathode, the end emission from the cathode is incorporated in order to enhance the self-insulated magnetic field and to reach Hull cut-off criterion. Using a 2-D PIC simulation, an output power of 1.16 GW at C band and 270 MW at X band in a MILO have been achieved. Further in 2001, Haworth *et al.*, have proposed an improved cathode design for long pulse MILO operation which has resulted in extending the radiated microwave pulse duration from 200ns to 400ns. This was accomplished by maximizing the emission uniformity in the launch point region of the cathode which in turn reduced the anode plasma formation. Haworth *et al*., in 2001 reported improved electrostatics design for MILO cathodes by implementing of miniature Pierce focusing electrodes on each end of the MILO cathode as a way to control the beam current density, to minimize anode plasma.

In 2005, a cooperative work was started in France with the aim of design a compact source MILO for defense application. Based on intensive numerical simulation, some refined prototypes have been built, mainly in the U.S., delivering 2 GW at a frequency slightly above 1 GHz. For compact MILO, the preliminary study on operating principles has shown the feasibility of such a device by getting simulated with 4 interaction cavities using PIC code MAGIC with output power >1.0 GW at a frequency of 2.44 GHz for operating voltage 500 kV, 45 kA. Further power output can be increased to 2 GW by optimizing the output coupling and reducing the beam loading effect. Detail study of the compact MILO interprets that the coupling between the geometrical sections which constitute the MILO tube can affect the interaction process and plays an active role on the stability of the MILO oscillation. Length is adjusted to optimize the output coupling through the output waveguide. In 2005, Fan *et al.* reported compact MILO with a new-type of beam dump. An improved MILO model consists of a novel beam dump, a one cavity RF choke section and a novel mode-transducing antenna, are introduced into the improved MILO. The improved MILO is investigated in detail using PIC simulation (KARAT code). The improved L-band MILO with RF power of 2 GW was investigated in detail using PIC KARAT code for the voltage of 520-540 kV and current of 58-62 kA. In 2007, Fan *et al.* reported simulation investigation of an improved MILO shown in Figure 1.7 operates at 1.76 GHz for 600 kV and 52 KA and achieved RF power of 4.2 GW with peak power conversion efficiency of 12%. A novel plate-inserted mode-transducing antenna, which is composed of a plate-inserted mode converter and a coaxial horn, is introduced into the improved MILO. TEM wave generated by the MILO propagates down the section of coaxial waveguide and is transformed into the TE_{11} mode by the novel plate-inserted mode converter, and then radiated by the coaxial horn antenna into air. Considering the above design influence the control of the symmetry of the emission of the electron beam and results in the proper operation of the device at the optimal state. Consequently, the device is expected to be shorter than the conventional MILO. Apart from the new-type beam dump mentioned above, a one-cavity RF choke section is also introduced into the improved MILO. Schematic of the conventional MILO is shown in Figure 1.6. This configuration has two disadvantages namely; the direction of the radiated microwave is different from the axial of the MILO and it is difficult to adjust the insulating magnetic field in the conventional MILO, because no part of it can be moved easily.

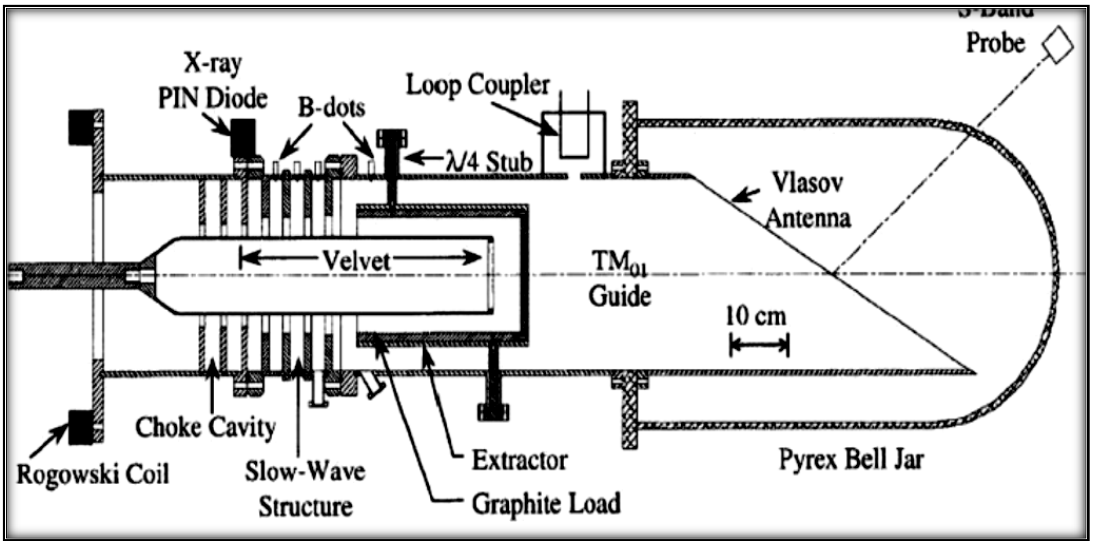

Figure 1.6: Schematic of conventional MILO [Haworth *et al.* (1998)].

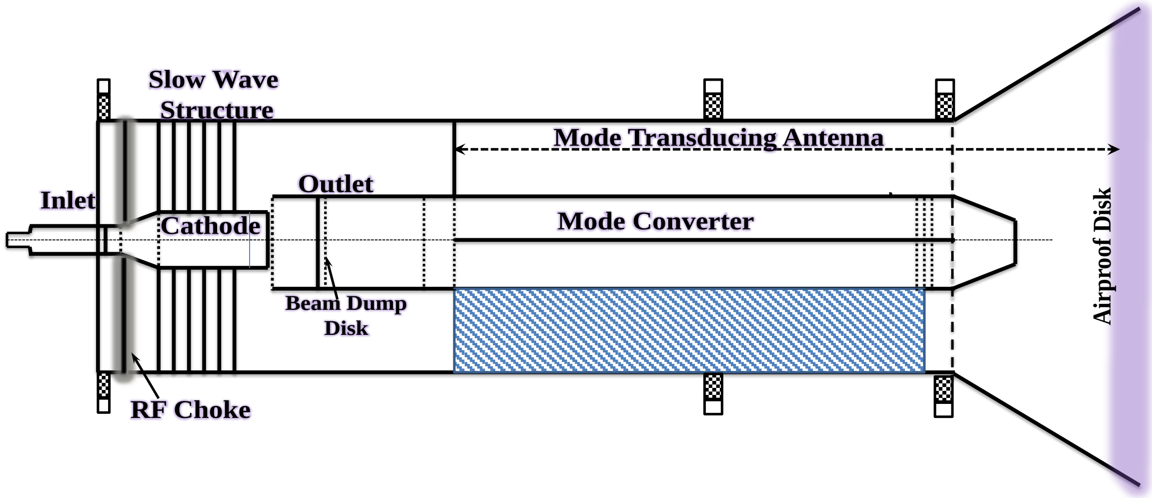

Figure 1.7: Schematics of improved MILO.

Zhang Xiao-ping *et al.*, in 2006 simulated (using KARAT Code) a novel compact P-band MILO at 630MHz with output power of 4.7GW and peak power conversion efficiency of 14.9% at 700 kV, 45 kA. This MILO has one choke vane and 4-interaction cavities. In 2007, R. Cousin *et al.,* reported gigawatt emission from a 2.4GHz compact MILO. During experiment, Figure 1.8 shown is driven by a low-impedance Marx generator. The main frequency at 2.4GHz is confirmed by measuring the emitted radiation by using both an in-vacuum antenna and a horn placed in the far-field region. The frequency response of the MILO is compared with 3D PIC simulation performed with MAGIC code. In the first experiment, a microwave output power of 1 GW has been obtained, which is in good agreement with the simulation value.

Fan *et al*., proposed a double band high power microwave source in which to increase the power conversion efficiency of MILO, an axially extracted virtual cathode oscillator is introduced to utilize the load current in the MILO. So, it is called MILO-VCO device. In this device MILO and VCO are operated synchronously

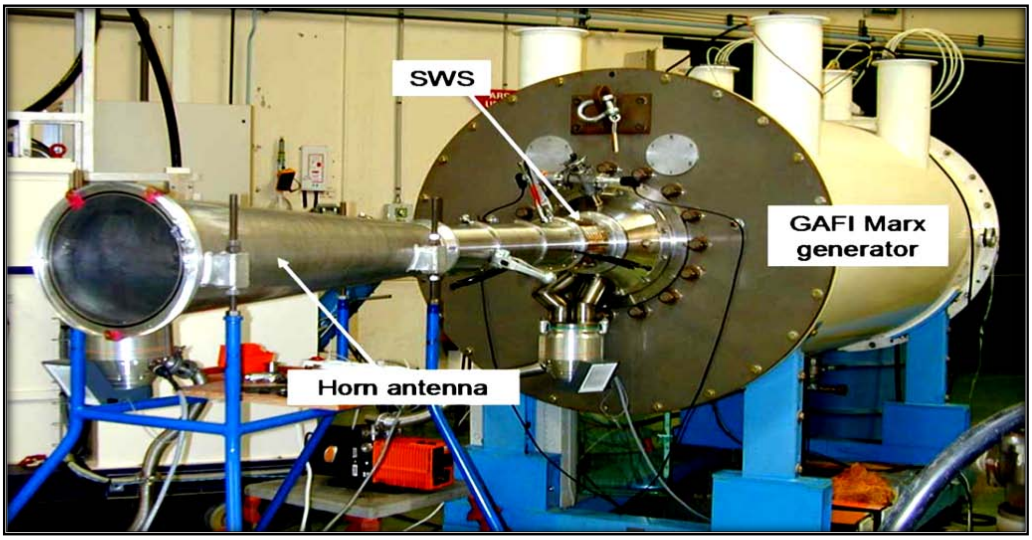

Figure 1.8: Experimental view of Compact MILO [Cousin *et al.* (2007)].

and generate HPM. During simulation of MILO-VCO, using KARAT code, peak RF output power of 5.22 GW with an efficiency of 16.3% is generated. In this MILO-VCO, peak power of MILO is 3.91GW at 1.76GHz while peak power of VCO is 1.33GW at 3.79GHz.During year 2008, Fan *et al.*, designed an X-band MILO considering the concept of Vircator-MILO. The model of the investigated *X*-band MILO is illustrated in Figure 1.9. It is composed of a coaxial diode and a load diode. The *X*-band MILO is a hybrid design using a RF choke section as well as a tapered cathode at the upstream boundary of the slow-wave structure (SWS) in the MILO of Lemke *et al.* and a tapered downstream SWS as well as a load region with an axial gap in the tapered MILO of Eastwood *et al.* In order to increase the length of the interaction region, a ten-cavity SWS is introduced to the X-band MILO.

During simulation, the X-band MILO, driven by a 720 kV, 53 kA electron beam, comes to a nonlinear steady state in 4.0 ns. High-power microwaves of TEM mode is generated with an average power of 4.1 GW, a frequency of 9.3 GHz, and power conversion efficiency of 10.8% in durations of 0-40 ns. During experiments, when the voltage is 400 kV and the current is 50 kA, the radiated microwave power

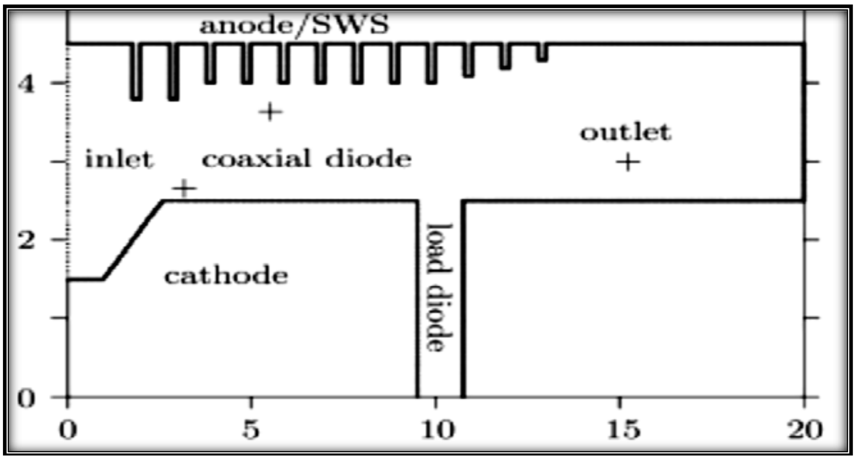

Figure 1.9: Schematic of X-Band MILO [Fan *et al*. (2008)].

reaches about 110MW and the dominating frequency is 9.7 GHz. Because the surfaces of the cathode end and the beam dump are destroyed, diode voltage cannot increase continuously. The experimental results are greatly different from the simulation predictions due to cathode flare formation and anode plasma formation.

W. Yang fabricated a C-Band MILO which does not have choke vane and impedance discontinuity at the launch point. There were only five vanes and four cavities in it. For an electron beam of 500 kV and 20 GW, by changing from one vane to two vanes having tapered radii in the extraction region and adjusting the axial width of the first vane, the output efficiency reached~10.5% at an output power of 2.1GW at 3.72 GHz. Elimination of the choke vanes and large coupling with the output section are the main improvements.

In the proposed C-band MILO choke vanes are eliminated shown in Figure 1.10. Choke vanes are used to improve the efficiency in an L-band MILO. However, in a C-band MILO, the cathode–anode gap is much smaller compared with that of an L-band MILO. The radius of the choke vane is several millimeters smaller than the vanes in the SWS region; thus, the choke vanes are much closer to the cathode. Therefore, problems, such as cathode and anode plasma formation, are more inclined

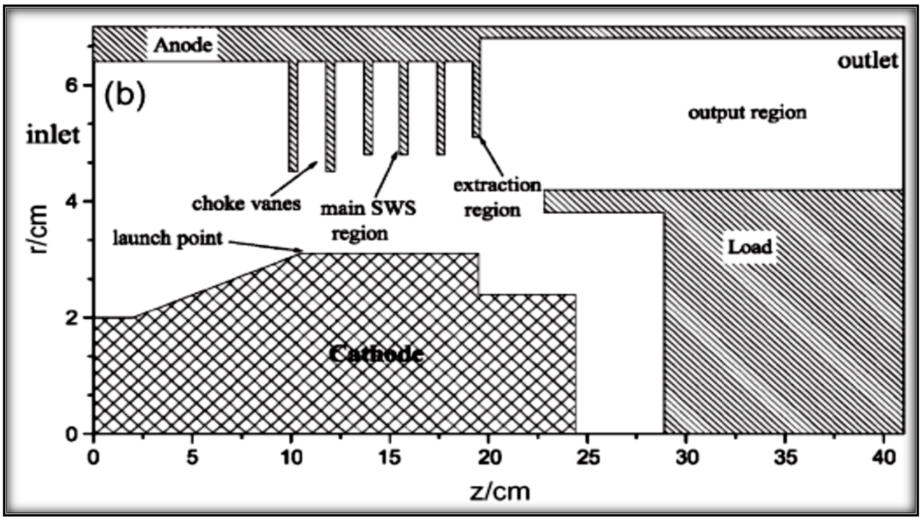

Figure 1.10: Schematic drawing of C-band MILO [Yang (2008)].

to appear. These problems will lead to the drop of output power and pulse shortening in the long-pulse operation. In 2008, Fan *et al.* proposed repetition rate operation of an improved magnetically insulated transmission line oscillator. This MILO is initially tested at 550 kV, 54 kA from 0.5 Hz to 3 Hz using velvet based and graphite cathode. Output power of 3.1 GW at 1.755 GHz was obtained with peak power conversion efficiency of 10.4%. It was found that shot to shot reproducibility is very good for graphite cathode comparing with velvet based cathode and the radiated microwave power is less than 1.0 dB during the bursts even when the device is operated at 20 Hz rep-rate. In 2009**,** Fan *et al.* reported an S-Band Tapered MILO shown in Figure 1.11, that produces an RF output peak power of 2GW, frequency of 2.63 GHz, and mode TM_{01} with beam to microwave power efficiency ~ 11%. Fan *et al.* concludes that the distance between the load support legs and the last vane can affect the operation characteristics of this device.

Dai-Bing Chen *et al.*, in 2009 presented a bi-frequency (BF) MILO with a novel idea of azimuthal partition to generate HPM with the two frequencies of 3.4GHz and 3.65GHz in a single device is put forward. According to this idea, a MILO is designed

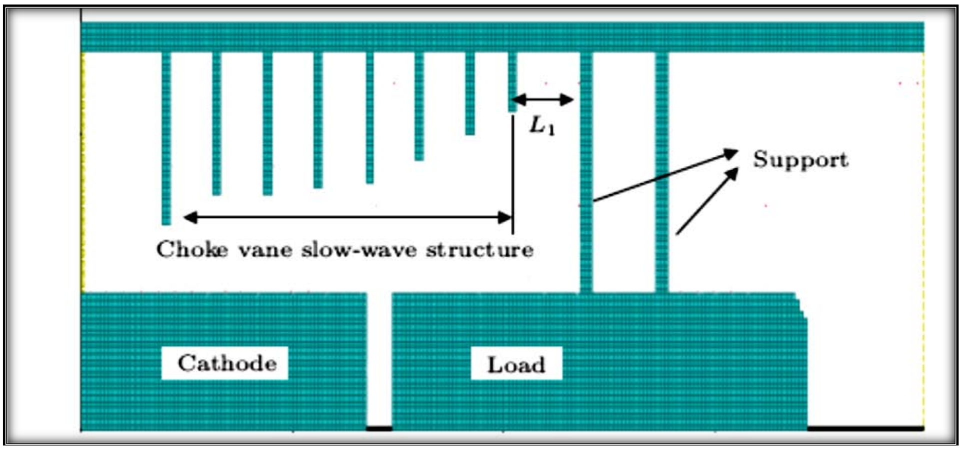

Figure 1.11: Schematic drawing of S-band tapered MILO [Fan et al. (2009)].

by tuning the cavity-depth of a conventional MILO in azimuthal direction such as self-insulated current, total anode current and total impedance nearly the same as those of a conventional MILO. Simulation results show that a C-band BFMILO stably yields an HPM output power of about 1.43GW when the electron beam voltage is 490 kV and the current is about 45 kA. The power conversion efficiency is about 6.5%. The amplitude difference between the two microwaves in the spectrum is about 0.4dB.Each frequency is distributed in its corresponding partition. Also in this particular year, Fen Qin *et al.*, introduces concept of L-Band ladder cathode MILO shown in Figure 1.12 with improved power conversion efficiency. Employing an electron beam of 568 kV, 53.3 kA, a TEM mode high-power microwave with output power of 5.5 GW, frequency of 1.2 GHz is obtained. The power conversion efficiency is 18.2%.

An improved BFMILO was simulated by Dong Wang *et al.*, in 2010 for generating microwave power at two frequencies of 1.21 GHz and 1.46 GHz. It is the intrinsic field distribution that has been found to be reason of low efficiency of original BFMILO. Introducing some modifications into the SWS region, an improved

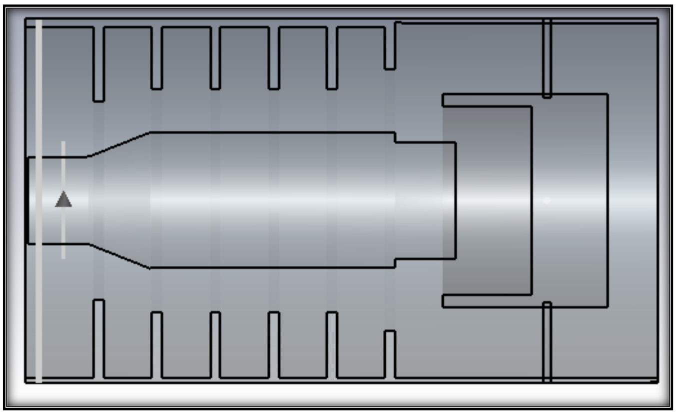

Figure 1.12: Schematic of Ladder-cathode MILO.

BFMILO is designed. High frequency analysis showed that it has a better field distribution than the original one. The improved BF-MILO yields microwave power of 2 GW while the output power is 1.7 GW for the original one for the same beam voltage of 445 kV and 39.7 kA.

To improve microwave output characteristics, Renzhen Xiao *et al.* reported an *X*-band magnetically insulated line oscillator MILO with a separate cathode. The separate cathode consists of three parts with gradually decreased radii, which are divided by two deep grooves, and only partial cathode surfaces are allowed to emit electrons. In particle-in-cell simulation, high-power microwave with a power of 6.9 GW, frequency of 9.26 GHz, and efficiency of 20.6% is generated, compared with that of 12.2% obtained in a conventional cathode *X*-band MILO, and the power ratio of the output transverse-electromagnetic mode to transverse-magnetic TM_{01} mode is increased from 4 to 27. Qin *et al.*, in 2011 introduced a novel method to depress higher order mode generation in MILO which is due to asymmetric beam emission or slightly asymmetric structure in MILO device. The excitation of higher order modes was depressed by adjusting the SWS and high power microwave in purified TEM mode was obtained. The simulated device showed that MILO oscillates at TM_{00} mode and successfully depressed the higher order mode HEM_{11} mode generation.

Smrity Dwivedi *et al.,* in 2012 proposed electromagnetic analysis of a disk loaded coaxial waveguiding structure for MILO excited in TM_{01} mode. The dispersion relation is obtained considering the continuity of the fields at the interface between these two regions. Also, structure has been simulated using CST microwave studio for the dispersion and interaction impedance characteristics. This study would help in understanding the physics and in selecting the coaxial disk loaded structure parameters for the use in MILO devices having reasonable RF growth rate in synchronism with electron beam. Wen *et al.,* in 2012, reported a novel MILO with stable frequency and high efficiency which is obtained by slotting plates to introduce 2-D periodic slow wave structure in the interaction field between the beam and microwave. PIC simulation indicates that HPM with pure frequency of 1.22 GHz and multimodes of TEM, TE_{11} and TE_{21} is generated and the peak power is increased to 2.8 GW from 2.4 GW compared with original MILO when the voltage is 450 kV and the current of 43 kA. The frequency can also be stable after asymmetrically excited. Zhou *et al.,* reported Investigation of High Impedance MILO with hollow load in 2012. A MILO with impedance of 30Ω and power conversion efficiency of 25% is estimated by PIC simulation. Compared with previous MILO, the anode current is reduced about 50% and doubles the power conversion efficiency while the power deposition on the anode is reduced nearly one half. The load current is reduced to 4.6 kA which is 17% of the total anode current. Finally, a hollow load is introduced to reduce the power deposition density on the load without decreasing the power conversion efficiency. For the voltage of 810 kV and current of 26.9 kA with an impedance of 30Ω, output power of 5.5GW at 1.74GHz has been obtained.

Wen *et al.,* has proposed the *Ku*-band MILO, in 2013 and investigated numerically and experimentally. Reflect cavities are introduced to reduce the field intensity between cathode and anode. In the PIC simulation, the *Ku*-band MILO generates power of 2.48 GW of 12.5 GHz, with the voltage is 478 kV and the current is 48.9 kA. After the collector improved, *Ku*-band of 12.9 GHz is generated, using the voltage and current of 539 kV and 57 kA. The peak power is 89 MW and pulse width is 15 ns at TM_{01} mode have been obtained.

Smrity Dwivedi *et al.*, in 2013, has optimized the dimensions of the S-band MILO using MAGIC PIC code for 600 kV,35 kA and enhanced the RF power performance. In this paper, a MILO device is analyzed for its designed value of 600 kV DC voltage and 35 kA current. The analysis predicts 1.0 GW RF output power, ~6% of overall efficiency of the device for the typical design parameters. The optimized S-band MILO structure provides the RF power output of 2 GW.

1.6 Motivation and Objectives of thesis

The motivation for research on high power MILO device is inspired from its potential applications particularly in Indian scenario. During the last few years, MILO has emerged as a compact and efficient high power microwave source are in demand for the recent upcoming applications, in directed energy weaponry systems. Significant works including theoretical, experimental and computer simulation have been carried out for the MILO performance improvement. Nevertheless, at present the designing of the MILO taking into account pulse shortening problem, shot-to-shot reproducibility remains a critical issue for its developers. This aspect perhaps motivated the author to associate, contribute and enhance the knowledge for this important problem in MILO. Maximizing power, lifetime of cathode and efficiency are still an active research area worldwide. These performances related issues of the MILO motivated the author to choose the current topic as his doctoral research work.

The prime objective of this thesis is to contribute research work pertaining to performance improvement in beam-wave interaction process in MILO, so that maximum power conversion efficiency can be achieved. In order to carry out the aforementioned work author optimizes RF interaction structure of MILO using equivalent circuit approach for beam absent and presence case. Coaxial periodic disc loaded structure operating in the TM_{01} mode is considered for analysis. The RF interaction structure is analyzed for its dispersion and impedance characteristics using equivalent circuit approach in terms of the series inductance and shunt capacitance per unit length of the equivalent line. This approach is handy, unlike in the field analysis, it is not required to simplify a complex dispersion relation which involves a $n \times m$ determinant.

1.7 Plan and Scope of thesis

Now-a-days, various technologies related to HPM sources have been revolutionized due to vast applications in civilian and military. Considering Indian scenario on MILO, it is still under evolution and several laboratories are contributing theoretical research work. MTRDC, DRDO, Bangalore is doing research related to the experimental and development work for the MILO. In the field of HPM source MILO, designing and experimental work is always a challenging task due to the involvement of various fields electromagnetic theory; charged particle; optics; dissipation of sufficient amount of power at anode; plasma formation; thermal effects at the load side etc. Therefore, to explore above mentioned parameters, it has been planned to further improve the analysis, design, simulation and experimental activities for MILO. A design methodology has been worked out and validated using the available commercially available CST-PIC simulation software. Different performance improvement techniques have also explored to improve the different structure parameters that result in improving power conversion efficiency. All the studies have been carried out for MILO oscillating in the π-mode. The research work is embodied in the form of the present doctoral thesis which is organized in the seven chapters.

Chapter 1 contains discussion pertaining to the need and salient features of HPM sources. Different applications of high power microwave are discussed along with the recent trends and usefulness of the MILO in today's scenario. In brief, operating principle of MILO is explained along with the working mechanism of different sub-assemblies. Historical development and literature review is also presented in this chapter. This review manifested about present status, issues and limitations as well as give information about different device versions for its performance improvement.

Chapter 2 presents the fundamental operations of crossed field device MILO. Field emission process from the cathode surface and magnetic insulation condition is described in detail. Flow mechanism of various currents inside the structure also taking into account during analysis. A simple and comprehensive synthesis approach is developed and described herewith. Starting with the basic fundamental Maxwell's equations and various boundary conditions, Hull cut-off condition and Hartree condition are obtained to find out the operating region for π-mode of oscillation. The field theory method is described to determine the electric and magnetic field profile for the coaxial disc loaded waveguide structure.

Chapter 3 describes the improved design methodology and PIC simulations procedure for the estimations of cold (electron beam absent) resonant frequency, excited modes, electric and magnetic fields profile of the structure along with the dispersion diagram for the L-Band MILO. Structure is modeled using improved design methodology. Considering CST-Particle studio, electron beam and RF wave interaction behavior including RF output power, efficiency and particle statistics at different interval of time for the L-Band MILO is also discussed. Finally, the simulated results are verified with those available in the published literature.

Chapter 4 covers the electromagnetic analysis of the disc-loaded coaxial waveguide structure using equivalent circuit approach instead of the modal matching technique. Disc-loaded cylindrical waveguide is an all metal structure, hence, can handle higher power and so used in the high power devices and systems. In MILO, disc-loaded waveguide is used as its RF interaction structure with an additional coaxial metallic cylinder at its center. The 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. A coaxial periodic disc loaded structure operating in the TM_{01} mode is analyzed. The structure is modeled using equivalent circuit approach in terms of the series inductance and shunt capacitance per unit length of the equivalent line. The dispersion relation and the characteristic impedance of the structure is obtained here applying the equivalent circuit approach and used to plot the dispersion characteristics, characteristic impedance as well as study the role of structure parameters to control their shape.

Chapter 5 includes the feedback of the cold or beam-absent analysis of the structure to its hot or beam-present analysis leading to the hot dispersion relation of the MILO, using equivalent circuit approach. and, in turn, the device temporal growth rate. This analysis is carried out to obtain the temporal growth rate, released RF energy, oscillation frequency and RF output power from RF interaction structure of MILO. For further rigorous and simplicity, here equivalent circuit approach is preferred. RF energy stored and transfer through the slow wave structure is calculated using equivalent circuit approach considering admittance of the cavity. Imaginary part of admittance represents energy stored or released from the cavity. Considering this concept and internal and external quality factor, RF energy stored and power is derived in this chapter. Analytical temporal growth rate and RF energy and power are found in good agreement with the published field analytical approach.

Chapter 6 deals with the performance and improvement in the working mechanisms of conventional MILO. This study further helps in improving power conversion efficiency of various MILO. This is possible through optimization of various structure parameters using design methodology presented in chapter 3 and validated this optimization study using RF analysis presented in chapter 5.

A summary of the works embodied in the present thesis are summarized in ***Chapter 7.*** The conclusions of the work are described and findings are discussed. Additionally, the limitations of the present study are discussed. The future scopes and extension of the present work is also outlined in this chapter.