Chapter 16

High Power Vacuum Tube Devices

—Romesh Chandra

In the electromagnetic spectrum the frequency range between 300 MHz to 300 GHz is known as microwave spectrum [1]. Vacuum tube devices which have output frequencies in between 300 MHz to 300 GHz frequency are known as microwave tubes [1-7]. Microwave spectrum is further divided into various microwave bands. The classification of microwave bands is given in table 16.1. Different microwave bands require different microwave tube devices. The widely used microwave devices are listed along with the frequency band in table 16.1.

It is important to learn basic mechanisms involved in the microwave generation prior to the discussion about the microwave tubes. The basic radiation mechanisms leading to the microwave generation are discussed in the next section.

16.1. Radiation from Charged Particles

A charged particle moving freely in an free space does not radiate. The free space refers to the absence of any medium of propagation and any external electric or magnetic field. In all the vacuum tube devices charged particle responsible for radiation are electrons. Any radiation generation mechanism requires two entities one being the electron and second one is any perturbation. The perturbation can be in form of any medium, photon or external field. The radiation generation mechanisms can be broadly classified in the following three categories on the basis of interaction mechanism,

1. Electron-medium interaction (Cherenkov and transition radiations).
2. Electron-external field interaction (Bremsstrahlung radiation).
3. Electron-photon interaction (Wave scattering).

The electron beam and generated radiation interaction can be given by [1],

$$\omega = k_z v_b + n\Omega \tag{16.1}$$

Here ω is the operating device frequency and Ω is the intrinsic frequency of the electron beam. Ω may be the plasma frequency, bunching frequency and cyclotron frequency depending upon the device. Here n is an integer and can assume values ..., -3, -2, -1, 0, 1, 2, 3, ..., k is the propagation constant of the radiated wave.

The radiation generated from a single electron is in the form of spontaneous emission of radiation, which is not sufficient for intense microwave generation. A collective phenomenon known as stimulated radiation is responsible for the microwave generation, in which electrons are forced to radiate in tandem under the influence of any discontinuity of medium or external field. The radiation generation interactions leading to microwave generation are given in detail in the following subsection.

Table 16.1. Frequency bands and corresponding widely used microwave devices [1].

Sr. No.	**Name of the Band**	**Frequency Range**	**Microwave Devices**
1.	P-band	0.3 – 1 GHz	Magnetrons
2.	L-band	1–2 GHz	Magnetically Insulated Line Oscillators (MILO), Vircators Magnetrons, Klystrons, Travelling Wave Tubes (TWT).
3.	S-band	2–4 GHz	Magnetrons, Backward Wave Oscillator (BWO), TWT, Cross Field Amplifiers (CFA), MILO, Klystrons, Vircators.
4.	C-band	4 – 8 GHz	Magnetrons, BWO, TWT, CFA, Klystrons, Vircators.
5.	X-band	8 – 12.5 GHz	BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers, Klystrons.
6.	Ku-band	12.5 – 18 GHz	BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers, Twistron.
7.	K-band	18 – 26.5 GHz	BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers.
8.	Ka-band	26.5 – 40 GHz	BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers, Transit Time Oscillator (TTO).
9.	V-band	40 – 75 GHz	BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers, Orotrons.
10.	W-band	75 – 110 GHz	Meta Material BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers.
11.	Millimeter Waves	110 – 300 GHz	Meta Material BWO, Gyro BWO, Gyrotrons, Gyro Amplifiers.

16.1.1. Plasma Devices

These are the devices in which the microwave generation takes place due to space charge characteristic of the electron beam itself. These devices are based on the principle of the space charge limited current [8]. In these devices an intense relativistic electron beam is forced through a mesh to propagate in a medium for which space charge limited current is much lower than the beam current. The electron beam cannot propagate through that medium and forms an electron beam cloud near mesh. This electron beam cloud keeps oscillating and microwaves are generated. Virtual cathode oscillators (Vircators) are most widely used plasma devices used for microwave generation [9]. These devices in detail will be discussed later in this chapter.

16.1.2. Cherenkov Interaction

In the Eq. (16.1) if n becomes zero, in this case for a free space radiation electron beam velocity must match the speed of the light. This condition cannot be achieved practically for a free electron moving in free space. In this condition radiated waves must be slowed down to match with the electron beam velocity. The slowing down of the microwave radiation may be achieved either by changing the propagation medium or by using special periodic metallic structures knows as slow wave structures (SWS). The radiation generated in slow wave structures is coherent and can be summed to generate the intense radiation to become stimulated Cherenkov radiation [10, 11]. The stimulated Cherenkov radiation and processes associated with microwave generation using this mechanism are given in detail in the following subsections.

A. Stimulated Cherenkov Radiation

We consider any stationary electron beam propagating through free space. This static beam can generate only static electric field and static magnetic field in the free space. If this electron beam is made to interact with any monochromatic electromagnetic field via Cherenkov interaction, then radiation is emitted. The fields of the emitted radiation do constructively superimpose to generate total enhanced field. This phenomenon is known as the stimulated Cherenkov radiation [11].

B. Interaction between Stationary Electron Beam and Monochromatic Radiation

The Cherenkov interaction between stationary electron beam and monochromatic radiation leads to following three processes responsible for microwave generation,

Electron Beam Modulation

If any stationary electron beam is synchronous to the microwave, the portion of electron beam synchronous with the decelerating phase gets decelerated and portion in synchronous with the accelerating phase gets accelerated. This leads to a velocity modulation in the otherwise stationary electron beam.

Electron Beam Bunching

Due to velocity modulation occurred under the influence of microwave, density redistribution happens in the electron beam. This leads to electron beam bunching.

Electron Beam Deceleration/Acceleration

Electron beam bunches decelerate or accelerate under the influence of the microwave field. This leads to a net energy exchange between electron beam and microwave.

C. Electron-Wave Synchronism in the Periodic SWS

In the periodic SWS, the relation between frequency of microwave and propagation constant is not linear. A typical Brillouin curve of the periodic SWS is given in Figure 16.1. The periodic nature of the SWS gives rise to space harmonics in the dispersion curve, which are separated by the vertical blue lines as shown in Figure 16.1. The red line shown in this Figure represents the light line. The dotted lines represent the electron beam lines of various energies. If the electron beam is synchronous with the microwave at a point where slope of dispersion curve is positive the group velocity is positive and microwaves are radiated in the forward direction. This point is marked as point 1 in Figure 16.1. At the points having negative slope group velocity is negative and microwaves are radiated in the backward direction to the electron beam. This point is marked as point 3 in Figure 16.1. For interaction at the peak and cusp of the dispersion curve the generated microwave have zero group velocity and are stored in the periodic SWS. These points are marked as point 2 and point 4 in Figure 16.1.

The nature of instability leading to microwave generation depends on the mutual orientation of electron beam velocity and microwave group velocity. If both the velocities are in the same direction in that case the strength of the wave packet generated by Cherenkov interaction increases with in frame of reference moving with electron beam velocity, but remains constant in laboratory frame of reference. This type of instability is known as **convective instability** and is utilized in amplifiers. If both velocities are in the opposite direction then strength of the generated wave packet grows in both the frame of references. This kind of instability is known as **absolute instability** and is used in microwave oscillators. To be particular in Figure 16.1 convective instability occurs at point 1 and absolute instabilities occur at points 2, 3 and 4 [11].

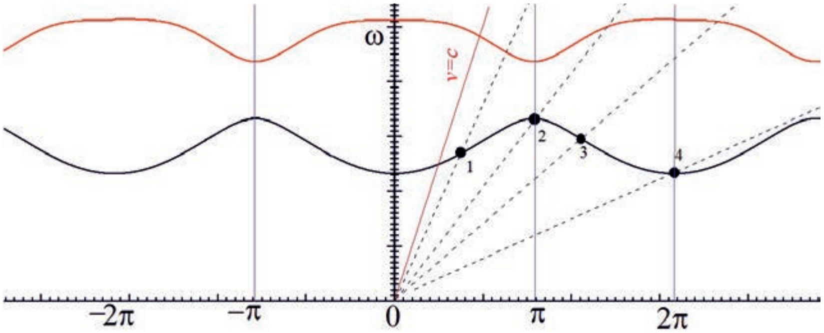

Figure 16.1. Brillouin diagram of the periodic SWS.

The devices based on the Cherenkov interaction are Cherenkov MASER, Travelling Wave Tubes (TWT) and Backward Wave Oscillators (BWO).

16.1.3. Bremsstrahlung

It is evident that the stationary beam can radiate only slow waves by interaction with any medium. From equation 16.1 fast wave radiation is possible if electrons have certain intrinsic frequency or acceleration induced by external field [11].

The intrinsic frequency Ω can be frequency of gyration $(eB/\gamma m)$ under the influence of external magnetic field. Usually cylindrical waveguides are utilized for fast wave interaction between electron beam and microwave. The typical Brillouin diagram of the Bremsstrahlung interaction between gyrating electron beam and modes of the cylindrical waveguide is shown in Figure 16.2.

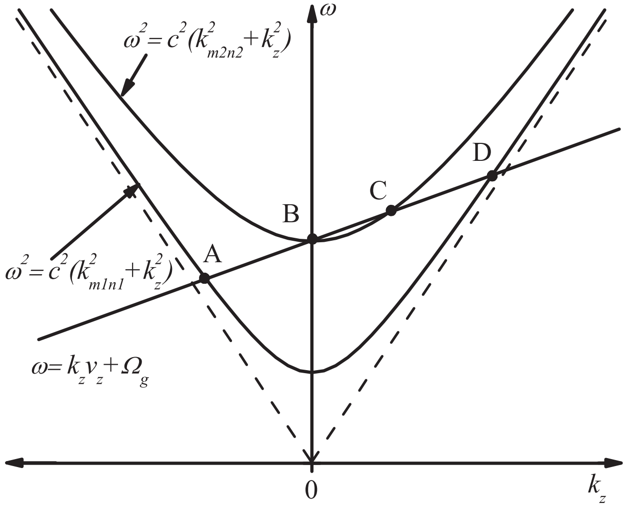

Figure 16.2. Brillouin diagram of the Bremsstrahlung interaction between gyrating electron beam and modes of the cylindrical waveguide. Dashed lines represent the light line and straight solid line represent the beam line Doppler shifted by frequency Ω_g.

In the similar analogy to Cherenkov interaction, the interaction instabilities at point C and D are convective in nature and are used in gyro amplifiers. The absolute instabilities are at points A and B. The gyro device operating at point B is known as Gyrotrons. The device operating at point A is Gyro-BWO.

Another most important practical device is Free electron laser in which electron beam propagates in a periodic trajectory under the influence of external magnetic field.

16.1.4. Transition Radiation

An electron radiates a transition radiation when it passes through an interface having different refractive indices at both sides on it or through some perturbation in the medium [12, 13]. In the practical microwave devices this disturbance in the medium is produced by the local electric field inside some microwave cavity. Klystron amplifiers are widely used transition radiation based devices. The Klystrons are already well known devices; hence these devices won't be discussed here.

A broad classification of the microwave devices based on their operating characteristics is given in Figure 16.3. It may be observed that vacuum tube device technology is extremely rich in terms of the number of devices. Devices exist from 300 MHz to 300 GHz covering whole spectrum of the microwave. It may also observe that devices are microwave band specific. This happens due to difficulty of manufacturing at higher frequencies and lowering of efficiencies due to enhanced surface resistance at higher frequencies.

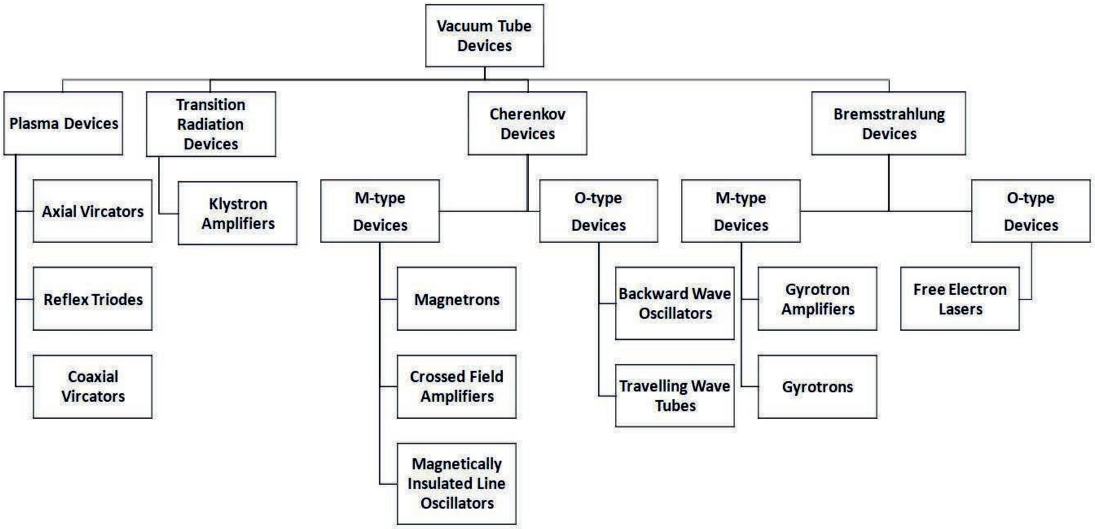

Figure 16.3. Classification of vacuum tube devices based on the mechanism of microwave generation.

The term high power vacuum devices refers to the devices having microwave power in excess of 100 MW. This definition does not consider the frequency of the microwaves generated. Hence to accommodate frequency in the definition of the high power vacuum tube devices a new term power frequency factor (Pf^2) has been defined. Devices having power frequency factor in excess of 10^{27} are known as high power vacuum tube devices [1, 11]. The Vacuum Tube devices developed worldwide are given in Table 16.2. This table represents the microwave power achieved from most commonly used high power vacuum tube devices like BWO, Magnetron and Magnetically Insulated Line Oscillator (MILO). It may be observed that maximum output power of various high power vacuum tube devices is in excess of 1 GW microwave power. Countries like USA, Russia earlier USSR and China are the leading countries in terms of vacuum tube device development capable of supplying microwave power in excess of 1 GW [14-17]. High power vacuum tube devices employ intense relativistic electron beam (IREB) for microwave generation. The self space charge induced by IREB affects the device efficiency significantly. To counter the radial motion of electrons due to self space charge force magnetic field is required. Development of the various kinds of microwave devices over the time has led to improvement in microwave conversion efficiency and reduction of the guiding magnetic field. It has enabled the use of permanent magnets to some extent in high power vacuum tube devices. The different kind of conventional and advance microwave tube devices will be discussed in this chapter.

Table 16.2. High Power Vacuum Tube devices development across the world.

Sr. No.	**Researchers**	**Country**	**Output Power**	**Efficiency**	**Frequency (GHz)**	**Year**
Backward Wave Oscillators						
1.	Moreland et al. [18]	USA/ RUSSIA	650 MW	25 %	9.5 X-band	1996
2.	Gunin et al. [19]	RUSSIA	3000 MW	22 %	X-band	1998
3.	S. A. Kitsanov et al. [20]	RUSSIA	4500 MW	31%	3.6 S-band	2005
4.	Klimov et al. [21]	RUSSIA	4300 MW	31%	9.4 X-band	2008
5.	R. Xiao et al. [22]	CHINA	4400 MW	32%	C-band	2010
6.	Y. Dang al. [23]	CHINA	1400 MW	40%	9.4 X-band	2018
7.	Romesh C. et al. [24]	INDIA	1100 MW	29 %	3.28 S-band	2015
8.	Romesh C. et al.	INDIA	1010 MW	22 %	9.18 X-band	2021

Relativistic Magnetrons						
1.	Palevsky and Bekefi [25]	USA/ RUSSIA	900 MW	25 %	2.5 S-band	1976
2.	A. Didenko [26]	RUSSIA	8000 MW	25 %	S-band & X-band	1990
3.	Edl Schimologulu [27]	USA	4500 MW	55%	2.4 S-band	2008
Magnetically Insulated Line Oscillator						
5.	M. Collins Clark [28]	USA	100 MW	5%	1.2 GHz L-band	1987
6.		USA/RUSSIA /CHINA	3000 MW	10%	L & S-band	2015

16.2. Plasma Devices

Plasma devices operate on the principle of virtual cathode formation due to beam current exceeding the space charge limited current in different geometries as discussed earlier. Depending on the geometry three kind of plasma devices are there for microwave generation.

16.2.1. Axial Virtual Cathode Oscillators

A schematic of the axial virtual cathode oscillator is shown in Figure 16.4. Electrons are emitted from anode and are accelerated up to anode mesh (Region-I). Electrons enter field free region-II with a kinetic energy equal to the accelerating voltage. The space charge limited current in region-I is given by,

$$I_I = \frac{4\epsilon_0}{9}\left(\frac{2e}{m}\right)^{\frac{1}{2}}\frac{\pi V^{1.5}(r+vt)^2}{(d-vt)^2} \tag{16.2}$$

In region-II space charge limited current is given by,

$$I_{scl} = \frac{17.1\times\left(\gamma_c^{2/3}-1\right)^{3/2}}{1+2\ln(r_0/r_b)} \tag{16.3}$$

For $I_I>>I_{SCL}$ the electron beam can't propagate in region-II and space charge cloud forms. These space charge clouds are called virtual cathodes. This virtual cathode oscillates in space to generate microwaves. Virtual cathode oscillations happen due to continuous loss of electrons from the cloud and after some time it starts oscillating with microwave frequency.

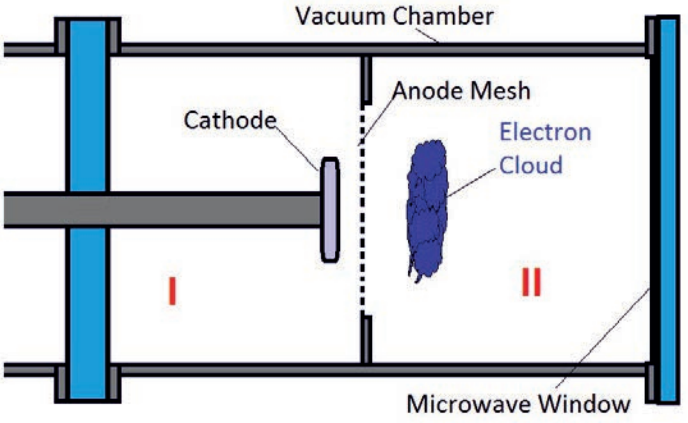

Figure 16.4. Axial Virtual cathode oscillator and cloud formation mechanism.

The microwave frequency of the axial virtual cathode oscillator lies in between the ω_p and $5\omega_p$, here $\omega_p = \sqrt{ne^2/m\varepsilon_0}$ is the plasma frequency of the electron beam. The efficiency of this device is poor (~2%) due to leakage of maximum electrons from the virtual cathode.

16.2.2. Reflex Triodes

The reflex triode geometry is shown in Figure 16.5. In case of reflex triode virtual cathode oscillators positive anode mesh is used and cathode is kept at ground. The electron beam accelerates up to mesh anode. Electrons after passing through mesh get decelerated due to applied electric field. The virtual cathode is formed at the location after mesh. The electrons keep oscillating between actual cathode and virtual cathode to generate microwaves.

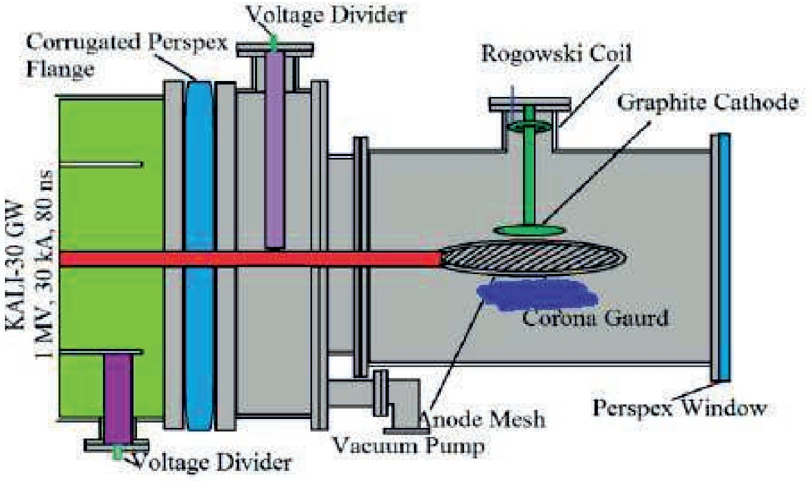

Figure 16.5. Schematic of the Reflex triode.

Virtual cathode formation is much stronger because electron leakage loss is very small, thus its Efficiency is slightly better (< 4%) than axial virtual cathode oscillators. The electrons keeps oscillating in between virtual cathode and actual cathode, with oscillations f_r given by [29],

$$f_r = \frac{v}{4d_{ak}} \tag{16.4}$$

Here v is the electron beam velocity, and d_{ak} is the anode cathode gap. The anode cathode gap taken here does consider the plasma expansion velocity.

The virtual cathode too oscillates in the reflex triodes, which oscillation frequency f_{vc} is given by [29],

$$f_{vc} = \frac{5}{4\pi}\left(\frac{e^2}{\gamma\varepsilon_0 m}\right)^{1/2}\left(\frac{1}{e\beta c}\right)^{1/2}\left\{\frac{4\varepsilon_0}{9}\left(\frac{2e}{m}\right)^{1/2}\frac{V^{3/2}}{d_{ak}^2}\right\}^{1/2} \tag{16.5}$$

Here V is the applied voltage between anode and cathode and and are the relativistic parameters of the electron beam. In both the Eqs. (16.4) and (16.5), the anode cathode gap d_{ak} is a time dependent quantity which changes during a single pulse as plasma expansion takes place. Thus the oscillation microwave frequency keeps changing and chirp like microwave pulses are obtained in the output of reflex triodes. The frequency at which the maximum microwave power is achieved lies in between f_r and f_{vc}.

16.2.3. Coaxial Virtual Cathode Oscillators

In coaxial virtual cathode oscillator device instead of planar geometry diode coaxial diodes are used as shown in Figure 16.6. Negative high voltage is applied at the cathode and ground mesh anode is used. Virtual cathode oscillates inside the anode mesh and due to faraday caging generated microwave can't escape radially through mesh. Microwaves are extracted from the antenna. Efficiency of the device is better (~4-6%) among all the virtual cathode oscillators.

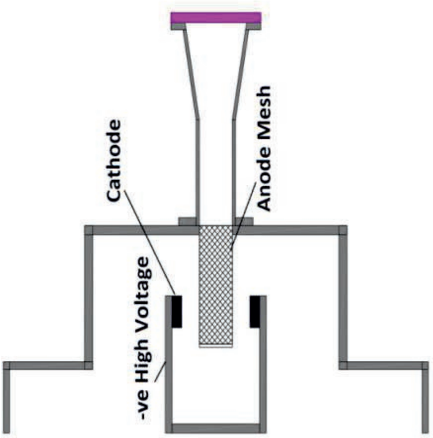

Figure 16.6. Schematic of the coaxial virtual cathode oscillators.

16.3. Cherenkov Devices

In Eq. (16.1) if $n = 0$, then the interaction is known as Cherenkov interaction. In this case only intrinsic frequency Ω, beam has is the plasma frequency which is very low in comparison to the operating frequency ω of the microwave tube. The Cherenkov devices can be further divided into two subcategories depending on the mutual orientation between electric field and magnetic field in the electron transport region. These two subcategories are M-type (Magnetron type) devices and linear beam tube devices also known as O-type devices. Both kinds of devices are widely used for various applications depending on the output frequency and other features like tunability and output power.

16.3.1. M-type Devices

In the M-type devices the electron beam transport happens in the region where applied electric field and magnetic field are perpendicular to each other.

A. Relativistic Magnetron

Relativistic magnetrons are cross field devices. These devices utilize vane kind of cavity as shown in Figure 16.7. If a cavity has *n*-vanes then it will have *(n/2+1)* normal modes of operation at one side of dispersion curve. The modes are given by *0, π/3, 2π/3* & *π* phase angles. Magnetrons operate in the standing wave mode hence π-mode operation is preferred. The central cylindrical shaft in the structure acts like a cathode and radial electrical field generates by application of high negative voltage on it. In perpendicular direction to the generated electric field a magnetic field B_z is applied. Thus electrons generated though explosive emission drift in the space between cathode and anode in $\boldsymbol{E}\times\boldsymbol{B}$ field. These electrons interact with the normal modes of the magnetron and suitable electron beam spoke formation takes place. The velocity of electron beam $\mathbf{E}\times\mathbf{B}/|\mathbf{B}|^2$ in the $\boldsymbol{E}\times\boldsymbol{B}$ field determines the modes of operation. For π-mode operation,

$$B_{min} = \frac{2mcR_a}{R_a^2 - R_c^2}(\gamma^2 - 1)^{1/2} \tag{16.4}$$

It is the minimum value of the magnetic field required so that electrons emitted from cathode doesn't reach anode directly. It is known as Hull Cutoff.

An upper limit comes on the magnetic field value above which electrons become too slow to achieve resonance with the desired mode. This is called Hartree line. The voltage corresponding to Hartree line is given by are given by,

$$\left(\frac{eV}{mc^2}\right) = \frac{eB_z\omega_n}{mc^2 n} R_a d_e - 1 + \sqrt{\left[1 + b_\varphi^2\right]\left[1 - \left(\frac{R_a\omega_n}{cn}\right)^2\right]} \tag{16.5}$$

Here $b_\varphi = \frac{I_b}{8.5} ln\left(\frac{R_a}{R_c}\right)$ and R_a and R_c are the anode and cathode radius respectively. $d_e = \frac{R_a^2 - R_c^2}{2R_c}$. The typical Hull cutoff and Hartree line for an eight vane cavity magnetron is given in Figure 16.7.

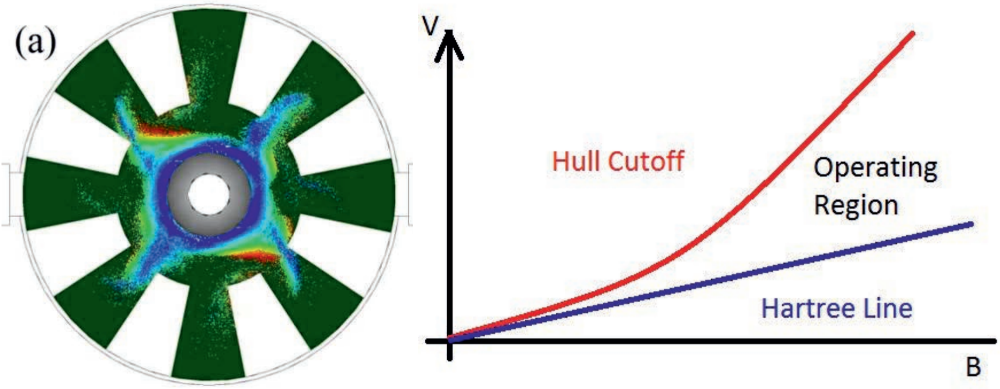

Figure 16.7. Electron beam spoke fomration in magnetrons for π-mode operation (left) and Bunnman Hartree Curve and Hull cutoff for a magnetron (right).

Electron beam spoke formation in six cavity magnetron is shown in Figure 16.7 as obtained from 3D PIC simulations. The output mode of microwave from magnetron if extracted radially is TE_{10} mode. In case of axial or diffraction output method it can be TE_{11} or TE_{m1}, here 2m is the number of cells in the magnetron structure.

B. Magnetically Insulated Line Oscillators

This device works on the principle of magnetic insulation due to self magnetic field of electron beam. Emission mostly takes place from the elevated portion of the cathode. Current values are from 40-70 kA for 350-600 kV diode voltage and are generated via explosive electron emission. A simulated structure is shown in figure. Initially electron beam propagates in radially straight direction then due to B_ϕ field, it starts bending and it flows grazing to the anode.

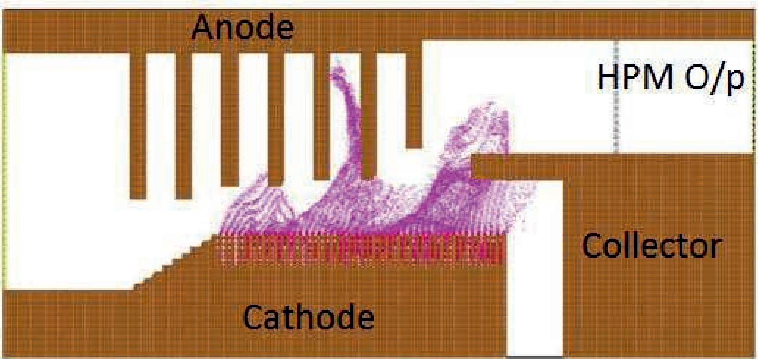

Figure 16.8. Schematic of a MILO device.

It interacts with SWS which is in resonant with the electron beam velocity and mode structure is established. The electron beam diode has impedance of 10-15 Ω in case of MILO.

The typical efficiency of MILO ranges from 6-12%. The output narrow frequency ranges from 1-12 GHz.

C. Crossed Field Amplifiers

Crossed field amplifiers (CFA) are the amplifier version of Magnetrons and are also known as Amplitrons. The schematic of eight cavity vane type CFA is given in Figure 16.9. From one cavity a microwave signal is fed and due to this input signal electron beam spokes are formed as shown in Figure 16.9. Microwave signal is extracted from other output port.

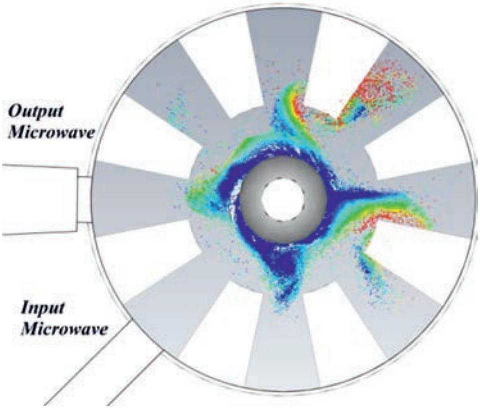

Figure 16.9. Schematic of the Crossed Field Amplifier showing spoke formation.

16.3.2. O-type Devices

In O-type devices electric field accelerating the electron is in the same direction as of the magnetic field if present. In such devices role of the magnetic field is limited to the guiding of electron beam. Thus these devices are also called linear beam tube devices. The linear beam tube devices can have possible configurations given in Figure 16.10. The Monotron and Klystron are transition radiation based devices. Travelling wave tubes and backward wave oscillators are Cherenkov devices and will be discussed here in detail.

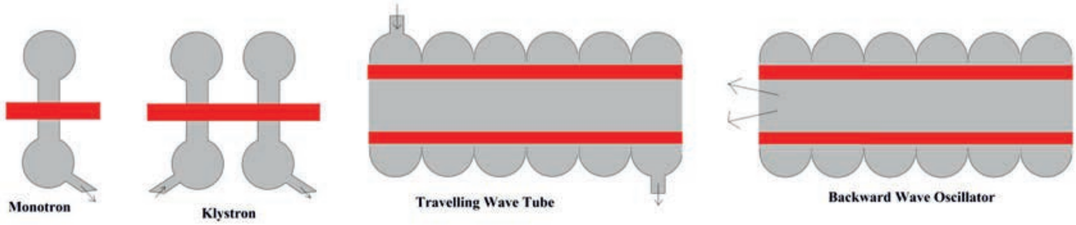

Figure 16.10. Classification of linear beam tube devices.

There are huge numbers of linear beam tube devices which are used in the microwave generation. Some of these devices which are widely used for microwave generation of high power magnitude would be discussed here.

A. Travelling Wave Tubes

Travelling wave tubes are widely used for microwave generation. These devices are basically amplifiers in which an input microwave signal modulates the electron beam. The schematic of these devices is shown in Figure 16.10. In this device the phase velocity of the microwave are matched with the electron beam velocity. Electron beam keeps losing its energy under the influence of the electric field exerted by microwaves and microwave intensity keeps growing towards the end of the travelling wave tubes. This enhanced microwave signal is extracted from travelling wave tube.

B. Backward Wave Oscillators

The schematic of the BWO device is shown in Figure 16.11. In case of backward wave oscillator an intense electron beam is guided by an axial strong magnetic field through a slow wave structure (SWS) which is resonant at angular frequency ω.

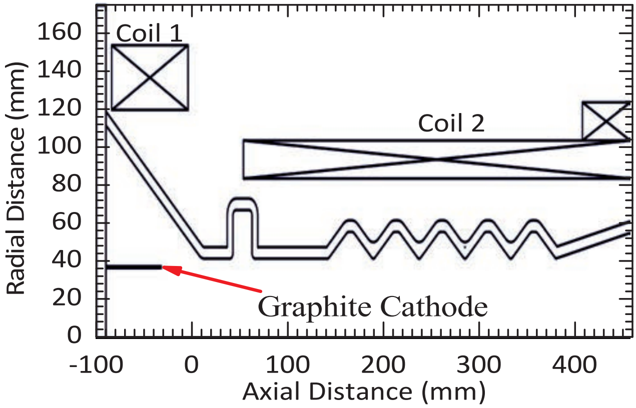

Figure 16.11. Schematic of the high power BWO device.

The only intrinsic frequency which electron beam has is its plasma frequency. The plasma frequency of the electron beam remains significantly lower than the SWS frequency ω. For RBWO interaction $n = 0$ in Eq. (16.1) and $\omega = k_z v_e$. Annular graphite cathode is used for electron beam generation which is guided through SWS by external guiding magnetic field. The generated microwaves propagate in opposite direction to the electron beam, which are reflected back by a suitable reflector and then extracted through antenna. In the BWO devices the phase velocity of the microwave inside SWS is matched with the electron beam velocity and group velocity of microwaves is in opposite direction to the electron beam. Thus for a BWO device,

$$v_e = v_p = \frac{\omega}{k_z} \tag{16.6}$$

In the above Eq. (16.6) v_e and v_p are the electron beam velocity and phase velocity of microwave respectively. k_z is the propagation constant $k_z = \frac{2\pi}{\emptyset_n}$. ϕ_n is the phase angle of the microwave inside the SWS. In case $\phi_n = \pi$, the BWO device is known as surface wave oscillator (SWO). The electron beam propagation inside the X-band BWO device is shown in Figure 16.12. This device has been modeled in PIC simulations and has successfully operated for microwave power in excess of 1.0 GW.

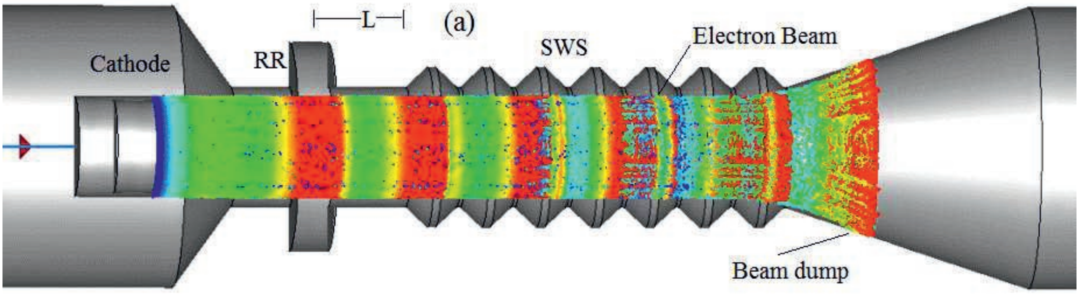

Figure 16.12. 3D Particle in Cell simulation of the X-band BWO device, showing electron beam modulation in it.

C. Twistron

Twistron devices are similar to BWO devices except for the part that the microwave extraction part is added in which microwave propagate as travelling waves. The schematic of the Twistron is shown in Figure 16.13. The extraction part is marked in this Figure. The extraction part is separated from the electron beam interaction region.

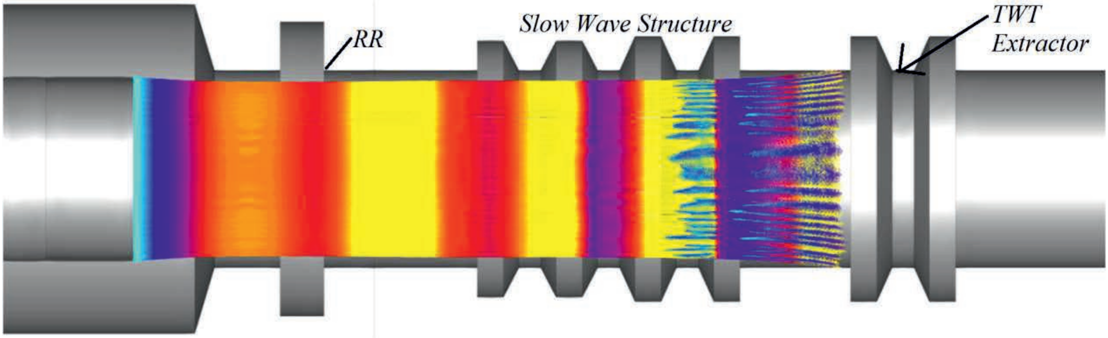

Figure 16.13. The schematic of Twistron for microwave generation. The color coding arranges the electron beam according to its energy. The extraction structure is TWT attached to right most side of structure.

D. Reltron

Reltron is a slow wave structure based vacuum tube device in which electron beam energy keeps increasing towards the end of the tube. The electron beam energy keeps increasing due to external applied voltage which is distributed across various components of the Reltron tube as shown in Figure 16.14.

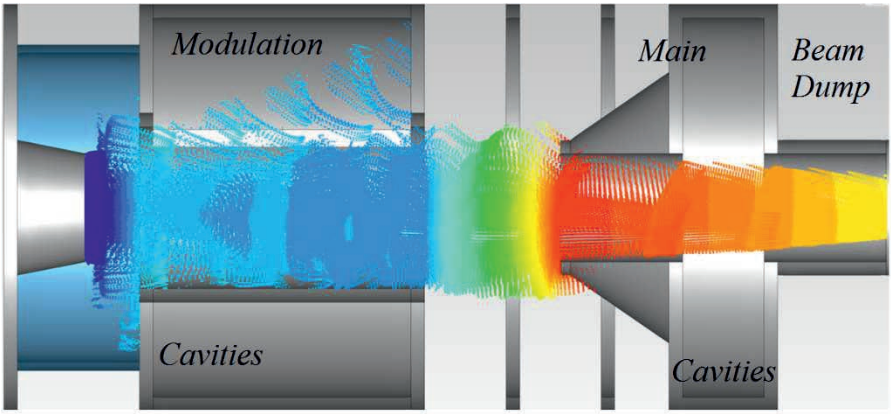

Figure 16.14. 3D Schematic of the Reltron tube showing its modulation cavities, main cavities and beam dump.

The Reltron tube has an advantage that it does not require external magnetic field for operation. Its efficiency is also high which can reach up to 25% to 35%. It has disadvantage of using meshes which may burn while operating for high beam currents.

16.4. Bremsstrahlung Devices

It is clear that stationary electron beam only interacts with slow waves. For microwave generation from fast wave modes it is required that electron beam must experience some periodic force or acceleration. This periodic force or acceleration constitutes the term Ω in equation 16.1. The periodic force may be electron beam gyration frequency under the influence of magnetic field or external periodic magnetic force exerted on the electron beam. Such interactions are known as Bremsstrahlung interactions. The Bremsstrahlung vacuum tubes devices have not been developed by APPD, BARC. These devices are briefly discussed here for the sake of completion.

16.4.1. Gyro-devices

The gyro-devices utilize the electron beam gyration frequency for the radiation generation. The interaction spaces usually are tubular cylindrical waveguides. Due to electron beam gyration the dispersion curve of the electron beam line is Doppler shifted by term $n\Omega$ in Eq. (16.1). The term n represents the harmonic of the modes inside the waveguide. The Brillouin diagram of the waveguide with electron beam gyrating with frequency is given in Figure 16.15. In this Figure 16.15, m_1, m_2, n_1 and n_2 are the waveguide indices in case of cylindrical waveguide. Generated radiation has a propagation constant k_z and it interacts with electron beam having axial velocity v_z. In this Figure at the points marked as point A and point B, the group velocity of electron beam matches with the electron beam velocity and this interaction is known as Gyrotron interaction. At point C electron beam velocity and group velocity of the microwave are in the same direction hence the interaction is gyro-TWT interaction. The gyro devices are also known as electron cyclotron masers (ECM).

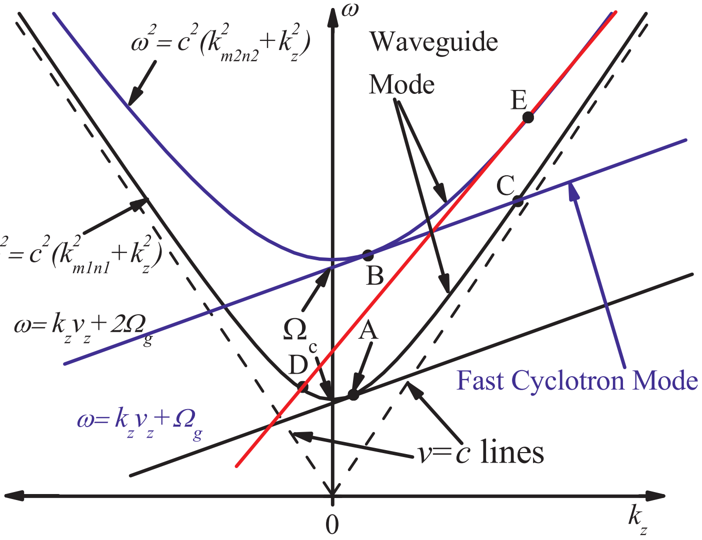

Figure 16.15. Typical Brillouin diagram of the gyro-devices. Point A represents Gyrotron interactions, Point B represents the gyro-TWT and point D represents gyro-BWO device interaction.

The schematic of any Gyro device is given in Figure 16.16. It consists of a Magnetron injection gun to supply electron beam in the interaction region. The design of the magnetron injection gun depends on the pitch factor ($\alpha = v_\perp / v_z$), which differs for various devices. The magnets are used to provide gyration radius to these electrons.

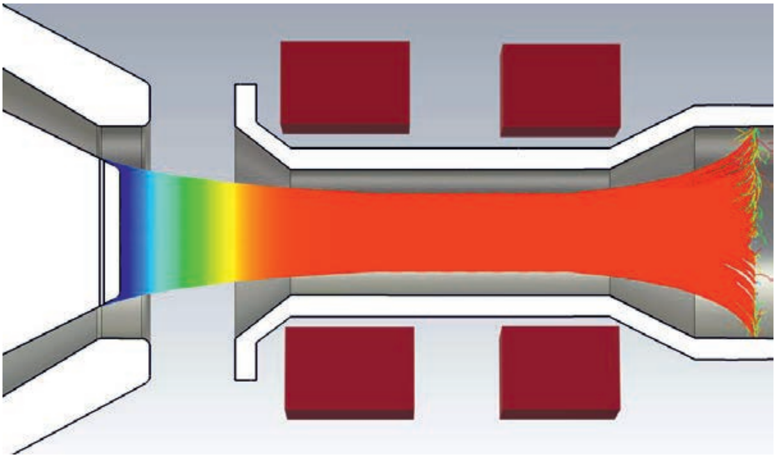

Figure 16.16. Schematic of a typical Gyro-device, showing electron beam trajectory inside the interaction space.

Depending on the electron beam energy and mode of operation these devices can have multiple configurations, which are listed below,

A. Gyrotrons and Gyro-klystrons

Gyrotron oscillators were the first devices developed under the gyro-device category in 1964 by Russian scientists [30]. In 1967 first Gyro-klystron experiments were performed. Both these devices work with only weakly relativistic electron beams having high pitch factor. Thus electrons have maximum energy in the transverse movement. In this case the Eq. (16.1) becomes,

$$\omega \approx n\Omega \tag{16.7}$$

In case of cylindrical tubes as shown in Figure 16.16 the operating mode is close to the waveguide cutoff and the frequency mismatch is very small.

B. Cyclotron Auto Resonance MASER

In case of relativistic electron beam interaction with the fast wave the Eq. (16.7) gets modified as given below,

$$\omega = \frac{n\Omega}{\gamma} \tag{16.8}$$

In this equation due to Gyrotron interaction, γ reduces rapidly thus the oscillation frequency increases rapidly in case of relativistic electron beam. Thus Gyrotron interaction is not suitable for relativistic electron beams. In case of relativistic electron beams the term $k_z v_b$is significant and cannot be ignored. In this case the appropriate resonance condition is given by,

$$\omega \cong k_z v_b + n\Omega_c \tag{16.9}$$

Here v_b is the axial velocity of electron beams and Ω_c is the cutoff frequency of the waveguide. Now if the device is operated at the upper bound of the dispersion curve where phase velocity of the operating mode approaches speed of light, in that case v_b keeps reducing due to microwave power extraction from the electron beam but the second term $n\Omega_c$ keeps increasing, which compensates for the decrement in the Doppler shift $k_z v_b$. Thus the frequency of the oscillation does not change at relativistic speeds too. This point is marked as point E in Figure 16.15. This device is known as Cyclotron Auto Resonance Maser (CARM) and is capable of providing 40% microwave conversion efficiency.

This device is currently widely used for sub Terahertz radiation generation using relativistic electron beam. The instability responsible for the radiation generation in CARM is convective in nature; hence Bragg reflectors are used for providing positive feedback to the system. In contrast to Gyrotrons, due to relativistic beams in CARM, pitch factor is generally much lower ($\alpha < 0.7$).

C. Gyro TWTs and Gyro BWOs

The point B in Figure 16.15 represents the gyro TWT instability. At this point the electron beam line is tangential to the waveguide structure dispersion curve at the operating point. This results in very efficient and high gain structure because at the resonance point the fast cyclotron mode and waveguide modes have similar phase velocity and also the group velocity of the wave is nearly equal to the electron beam axial velocity v_z. To benefit from the auto resonance the cutoff frequency of the waveguide mode should be reduced in comparison to the cyclotron frequency. Due to absence of any resonant structures in the Gyro TWTs it is possible to operate it over a much larger band-width.

If electron beam velocity and/or magnetic field magnitude are chosen in such a way that electron beam Doppler line intersects the waveguide dispersion curve having negative phase velocity, then gyro-BWO instability occurs in the electron beam. The Gyro-BWO device is similar to the Cherenkov BWO device except for the fact that in gyro-BWO device both phase velocity and group velocity of microwaves have negative sign. The interaction point is marked as point D in Figure 16.15.

The electron beam in all the mentioned gyro-devices discussed above cannot be ultra-relativistic. For ultra relativistic electron beams the change in relativistic constant γ during the operation becomes very significant and this increases the electron beam intrinsic frequency (Ω). Thus the resonance condition between electron beam and generated radiation gets disturbed. This limits the maximum output power from the gyro-devices. To increase the radiation intensity further free electron lasers have been introduced.

16.4.2. Synchrotron Radiation

The high power vacuum tube devices available in the various parts of the electromagnetic spectrum are shown in the Figure 16.17. The unavailability of vacuum tube devices in the sub Terahertz, Terahertz and infrared regions is quite evident from this graph. Devices based on the synchrotron radiation to operate in frequency range starting from microwave to X-ray region of electromagnetic spectrum.

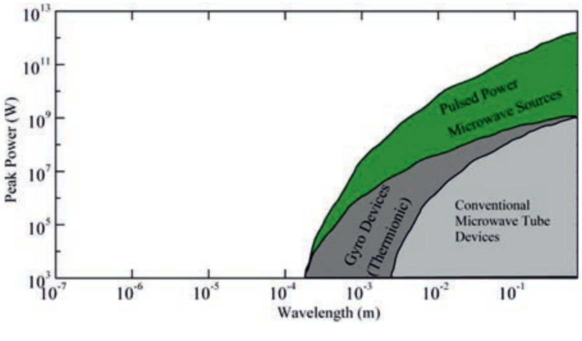

Figure 16.17. Vacuum tube devices operating in various regions of the electromagnetic spectrum.

When electrons or charged particles moving at relativistic speed are forced to follow curved trajectory by external magnetic field the synchrotron radiation is emitted in the direction of motion of electrons. For synchrotron radiation generation particle accelerators or storage rings are used. The synchrotron radiation is extremely intense can have spectral range from THz to X-ray frequencies.

The synchrotron radiation was observed in 1947 for the first time at the General Electric Synchrotron, USA. Firstly it was seen as the drawback in the high energy accelerators as a major portion of the particle energy was lost through this channel of synchrotron radiation. Now days the synchrotron radiation is used to study the structural details at the molecular and atomic level, surface properties of the materials, thin films and complex protein structures. After the discovery in 1947, the synchrotron radiation from designed accelerators was used in parasitic mode during high energy physics experiments. These machines known as **first generation synchrotron sources** were not primarily designed for the synchrotron radiation. In the **second generation devices** bending magnets were used for radiation generation in storage rings and high energy accelerators. In the second generation sources, devices like high magnetic field wigglers were used for synchrotron radiation generation. In the **third generation sources,** optimization of magnetic field devices, like wiggler and Undulator led to insertion of these devices in the straight section of storage rings. The free electron lasers (FELs) are the **fourth generation devices**.

16.5. Applications of High Power Vacuum Tube Devices

Electronic components when subject to huge amount of electric field, tends to malfunction or may even suffer complete damage. This phenomenon is known as electromagnetic damage. This may be used for destroying any distant electronic circuit. Required high field values can be obtained using vacuum tube devices only. At 3 GHz frequency damage threshold of the personal computers is 3 kV/m.

Vacuum tube devices have many possible applications like Electromagnetic damage to Electronics, Electronic Vulnerability testing of electronic components, Plasma microwave interaction and powerful Nanosecond RADARS.

Very High power vacuum tube devices having very high output power from each of the device can be used to heat up any plasma to initiate fusion. Vacuum tube devices can also be used to study nonlinear behavior of plasma under intense electromagnetic radiation.

RADARs are used for range measurement and detection of any flying object or ground based moving object. Since high power pulses from vacuum tube devices are inherently <30-100 ns and output power may reach up to few GW. Thus detection range and resolution gets improved by using a high power vacuum tube source as the radiator in RADARs.

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Tutorials

[1] If spatial variation of the electromagnetic field is given, then how to confirm whether this field is radiative or not?

[2] For a 100 mm diameter 400 keV electron beam, propagating in a 150 mm diameter cylindrical pipe, estimate the space charge limited current of the geometry.

[3] For a surface wave oscillator operating at 400 kV with output microwave at 3 GHz, estimate the pitch of the slow wave structure used in the surface wave oscillator.