STUDIES ON
CERENKOV FREE ELECTRON LASER

By

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CERTIFICATE

This is to certify that the thesis entitled "Studies on Cerenkov Free Electron laser" being submitted by Ganeswar Mishra to the Indian Institute of Technology, Delhi for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by him.

Ganeswar Mishra has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge, has reached the requisite standard.

The results contained in this thesis have not been submitted in part or in full, to any other University or Institute for the award of any degree or diploma.

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PREFACE

Millimeter and submillimeter waves are attractive candidates for broadband communication and precision radar. In recent years, their potential for supplementary heating of thermonuclear fusion devices, e.g. tokamak, inertial confinement schemes and strategic defence initiative (SDI) has also been realised. Consequently extensive efforts have been made throughout the world during the last two decades to develop high power sources at these wavelengths. At longer wavelengths ($\lambda \gtrsim 1$ cm) there exist conventional sources of electromagnetic radiation, e.g. klystrons, magnetrons and travelling wave tubes operating successfully over the last 4-5 decades with high efficiency giving high powers. As the wavelength of the radiation approaches the millimeter range, the efficiency falls off rapidly. At very short wavelengths ($\lambda \lesssim 10\ \mu m$) there are conventional lasers giving high powers though not at high efficiency, η ($\eta < 1$ %). However, lasers do not operate in the millimeter and submillimeter band. For quite some time this band remained devoid of high power sources. A major breakthrough was achieved by the discovery of gyrotrons[1-4] and later free electron lasers[5-10]. These devices are based on the extraction of energy from relativistic electron beams via coherent emissions. Considerable advances have been made over the years in the relativistic electron beam technology

(REB); and now one can have electron beams of several tens of KA current and several MeV voltages with the energy spread < 1%.

A Gyrotron[11-17] works on the principle of electron cyclotron resonance maser instability. It consists of a beam of monoenergetic electrons streaming and gyrating about an external magnetic field. The electrons behave as individual oscillators gyrating about the magnetic field Bo $\hat{z}$ with a rotation frequency $\omega_R = \omega_c/\gamma$, where $\omega_c = |e|Bo/mc$ is the electron cyclotron frequency, e, m_o,c are the electron charge, rest mass and the light velocity respectively. γ is the relativistic gamma factor. The electron rotation frequency ω_R is a function of electron energy. Initially the phases of the electrons in their cyclotron orbits are random, so no radiation is emitted. The introduction of an electromagnetic field primarily polarised in the transverse direction can alter the particle orbits. With the initial polarisation (shown as in Fig. 1), those particles in the upper half ($x > 0$) lose energy and therefore increase their rotational frequency. Those in the lower half plane gain energy and decrease their rotation frequency. The variation in the electrons rotation frequency results in phase bunching such that the electrons radiate coherently at the frequency $\omega = s\omega_R (s = 1,2...)$. If the wave frequency is slightly greater than the average electron rotation

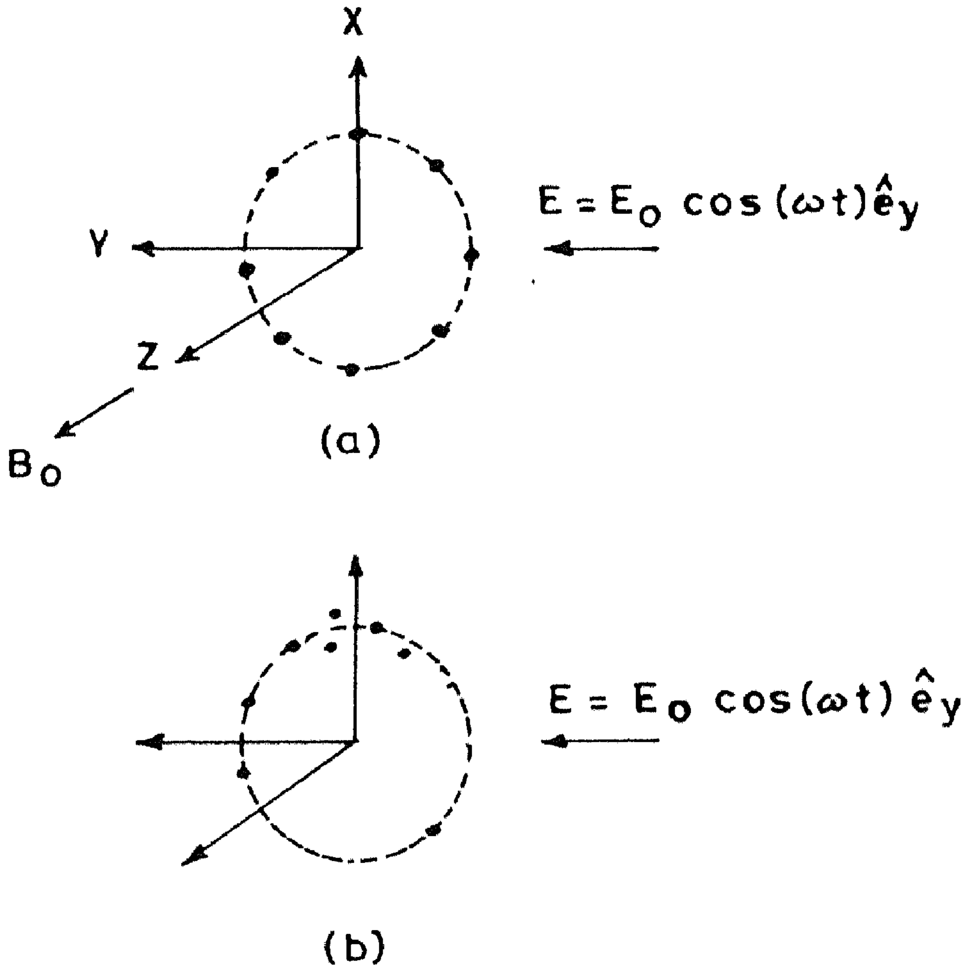


Fig. 1

(a) Initial electron phase distribution&field polarization

(b) Electron distribution after an integral number of wave periods for $\omega \geqslant \omega_R$.

frequency i.e. $\omega > \omega_R$, the phase of the bunches is such that the imposed radiation field is amplified. The primary source of radiation energy in the cyclotron resonance maser is the electrons gyrational energy. For high efficiency operation it is necessary that the ratio of the transverse to the longitudinal velocity ($V_\perp / V_\parallel$) be large.

A free electron laser[17-22] consists of three basic components : an accelerator to produce the electron beam, a wiggler magnet and a radiation field. The wiggler magnet consists of a series of alternating magnet poles which produces a magnetic field directed up and down along the length of the wiggler. As the injected electrons travel through the wiggler field they undergo transverse oscillations. Initially the electrons are randomly phased generating spontaneous magnetic bremsstrahlung radiation. The stimulated emission is caused by the axial bunching of the electrons. In the presence of a radiation field the wiggler electrons experience an axial ponderomotive force travelling very close to that of the beam. Depending on their phase, some electrons are decelerated while others are accelerated. Those that are decelerated move closer to resonance while those that are accelerated get away from resonance. The decelerated electrons fall into the wave potential and become bunched. When beam velocity is slightly higher than that of the ponderomotive wave, more electrons are decelerated than accelerated, hence net energy is transferred by the decelerated electrons to the radiation field which in turn enhances the electron density modulation and further increases the coherence of the growing radiation field.

Cerenkov free electron laser is another exciting device. It uses a dielectric lined resonator as a slow wave structure. When a relativistic electron beam propagates through it with a velocity greater than the phase velocity of the TM mode, it emits coherent radiation via cerenkov resonance. The use of cerenkov interaction as a possible source of microwaves was first introduced by Ginzburg[23] in 1947. Later Abele[24] showed that cerenkov radiation produced in a waveguide has a discrete spectrum. However the general idea that cerenkov radiation could be used to obtain laser action by stimulated emission process came much later. The first theoretical prediction and experimental demonstration of cerenkov free electron laser scheme were made by Walsh etal.[25-26] in 1977. They obtained 1 MW of coherent microwave power at 60 GHz with beam current 10KA, beam energy 0.5 MV using a cylindrical waveguide with annular dielectric layer. Later in 1981, Felch etal.[27] using cylindrical dielectric lined resonator produced high frequency microwave radiation in excess of 150 GHz with IKW power by interaction of 150KV, 20A electron beam with higher order waveguide modes. Since then several authors have reported their works on cerenkov free electron laser.[28-41]

Due to their unique technology, undulator and cerenkov free electron lasers offer several advantages relative to conventional lasers. These include wavelength tunability, high power, good optical beam quality and high efficiency.

One may view the process of cerenkov emission quantum mechanically as follows. Let an electron moving with velocity $\vec{V}_b$, radiate a photon of energy $\hbar\omega$, momentum $\hbar\vec{k}$. The energy and momentum of the electron after emission are

$$\varepsilon = \frac{1}{2} mV_b^2 - \hbar\omega \tag{1}$$

$$\vec{P} = m\vec{V}_b - \hbar k \tag{2}$$

since $\varepsilon = p^2/2m$, we obtain,

$$\omega = \vec{k}.\vec{V}_b \tag{3}$$

i.e. the component of the electron velocity in the direction of propagation of radiation must be equal to the phase velocity (ω/k) of the radiation. If the medium of propagation of radiation is vacuum then $\omega/k = c$ and condition (3) cannot be satisfied because the electron velocity can never exceed the velocity of light in the structure. Hence to achieve emission by electrons at the expense of their dc motion, the medium of interaction must have a refractive index greater than unity. A commonly used system is a cylindrical waveguide filled with a dielectric of dielectric constant, ($\varepsilon > 1$) having a hole in the center for the propagation of the electron beam. This describes the partially dielectric lined waveguide commonly employed in a cerenkov free electron laser study.

The physical mechanism of the stimulated emission process in a cerenkov free electron laser can be explained in the following manner[28]. Assume that the electrons are randomly phased with respect to the radiation field when they enter the resonator. Those electrons at near synchronous speeds with the radiation do not feel a rapidly fluctuating field and can exchange energy with the wave. Depending on its phase velocity, it will be either accelerated or decelerated in the radiation field. The radiation thus introduces a momentum modulation on the beam. In order to conserve the particle flux, there will be a corresponding oscillation in density which causes a bunching of the beam on the order of the radiation wavelength. (Fig. 2a) If the electrons travel at exactly the same speed as the radiation just as many electrons will be accelerated as decelerated and there will be no net energy exchanged, (Fig. 2b). If electrons travel slightly slower than the radiation then the bunching will occur in the accelerating phase of

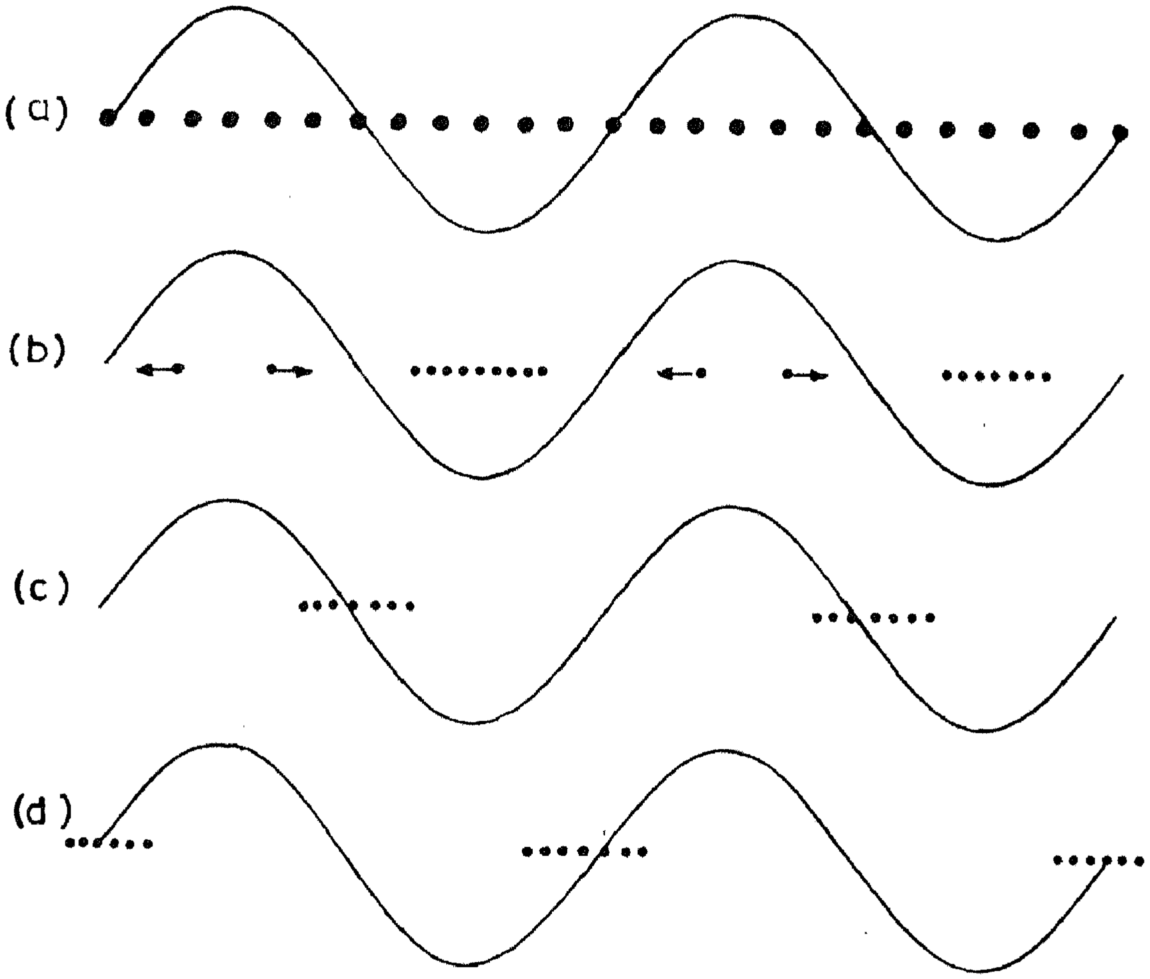
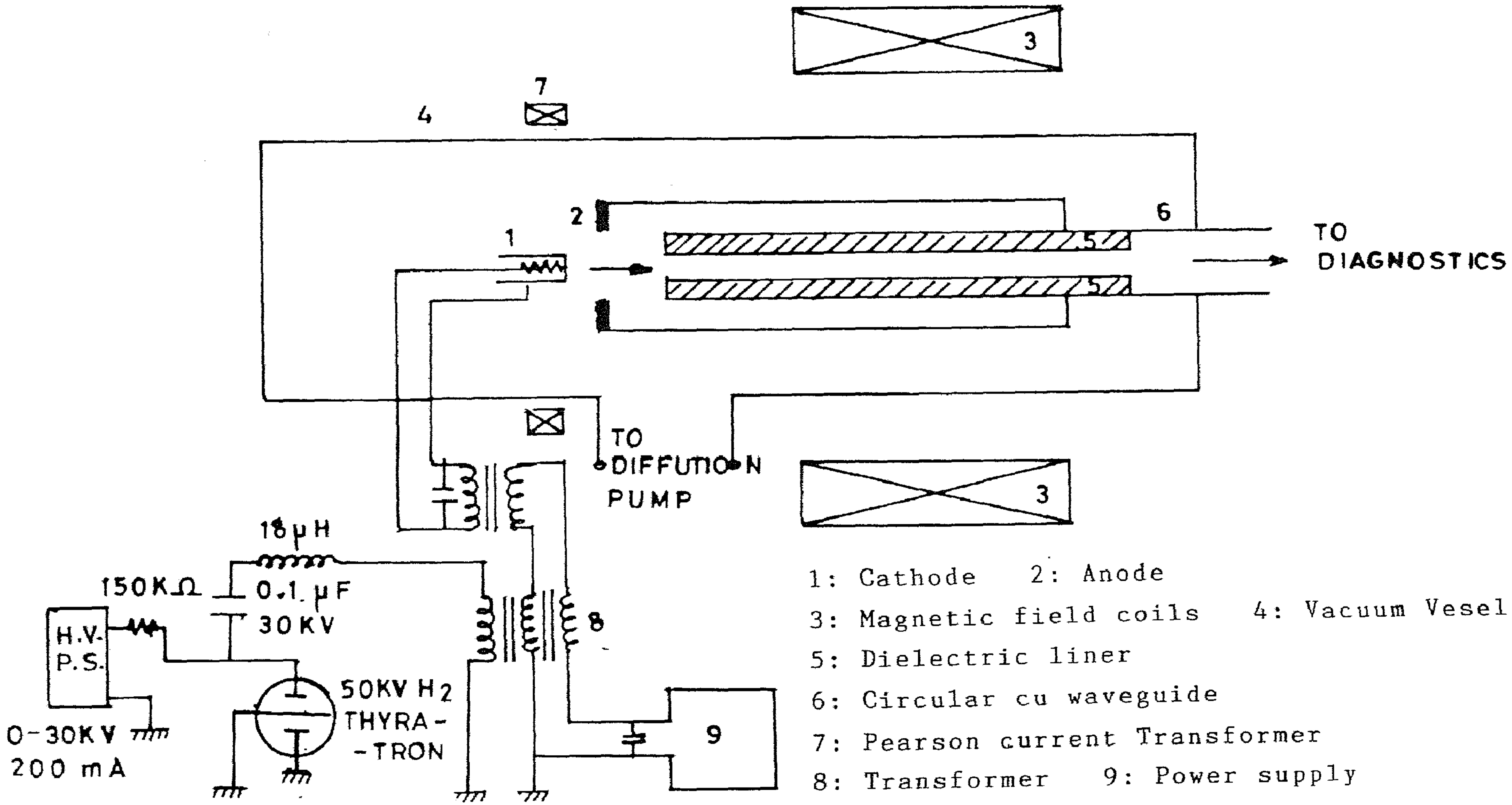


Fig. 2

Schematic of Electron Bunching.

the wave (Fig. 2c). More electrons will be accelerated at the expense of the wave amplitude and this is analogous to landau damping. However if the electrons travel slightly faster than the wave they will be bunched in its retarding phase and more electrons will be decelerated (Fig. 3d) by the process. This net loss in electron energy is manifested in the growth of the radiation amplitude and this is the mechanism for the stimulated radiation process in a cerenkov free electron laser device. Thus instead of each electron acting as a single independent radiation source, the electrons form bunches and radiate coherently thereby greatly enhancing the output.

A schematic of a cerenkov free electron laser is shown in Fig. (3). The slow wave structure is a dielectric lined cylindrical waveguide. The dielectric is chosen to be relatively lossless in the wavelength region of interest and the ease of fabrication of the film is given high consideration. A general technique for coating the dielectric inside the waveguide has been described by Johnson[28]. Dielectric materials of permittivity $\varepsilon = 2.12$ (TPX), $\varepsilon = 3.78$(Quartz), $\varepsilon=5$ (stycast), $\varepsilon = 4.2$ (Boron nitride) of several thickness have been employed in the experiments. The resonator geometry appropriate to the experiment i.e. cylindrical or flat-plate must be chosen. All the earlier experiments have been carried out with



1: Cathode 2: Anode
3: Magnetic field coils 4: Vacuum Vesel
5: Dielectric liner
6: Circular cu waveguide
7: Pearson current Transformer
8: Transformer 9: Power supply

Fig. 3

Schematic diagram of experimental apparatus for Cerenkov microwave generation, courtsyFelch etal[2] cylindrical geometry[27-32]. In an infrared experiment the dielectric film thickness is necessarily small (< 10 microns). Cylinders of this thickness are difficult to fabricate. In addition since the inner diameter must also be as small as possible to achieve reasonable beam-dielectric coupling, the focussing requirements are severe. For these reasons rectangular dielectric lined waveguides have been preferred in all latter experiments[33-34]. A schematic diagram of the electron beam generator and the resonator structure has outlined by Felch etal[27] & Garate etal.[31-32] In the experiments by Garate etal[31] in 1985, the cathode used was barium-oxide coated and produced current densities of about 10 A/cm^2. The output voltage pulse was varied from 0 to 300 KV. The electron beam was accelerated from the cathode through a hole in the molybdenum anode and into the boron nitride lined waveguide. In a latter experiment by Garate etal[32], the cathode was hemispherical with a radius of curvature of 3cm and was separated from the concave anode of 6mm diameter aperture. Both the cathode and the anode were made of graphite. This diode configuration produced 1.4 KA current at 1.2 MV. An axial magnetic field (5-8 KG) provided by external magnetic field coils guides the beam through the waveguide. The microwave radiation produced was guided from the interaction region through a lens-shaped Teflon vacuum Window into free space. Power measurements were made by using crystal detectors and attenuators in suitable waveguide mounts. Frequency measurements were made by using a series of high-pass filters or by using a microwave fabryperot interoferometer or by a diffraction grating spectrometer.

For a large variety of practical waveguides the dispersion relation is obtained by matching appropriate boundary conditions which must be satisfied by fields determined from Maxwell equations. In a hollow metallic waveguide two distinct types of mode propagation occurs.

(i) Transverse electric wave (TE) with $E_z = 0$ but $B_z \neq 0$.

(ii) Transverse magnetic(TM) wave with $E_z \neq 0$ but $B_z=0$.

There is a third field configuration called transverse electromagnetic wave (TEM) with nonzero transverse components only i.e. $E_z = 0$, $B_z = 0$. This mode may propagate in the open planar geometries and co-axial transmission lines but in closed metallic waveguides of arbitrary cross-section either TE or TM mode propagation occurs. There are however some practical waveguides for example dielectric waveguides or helix where a TE (or TM) wave does not by itself satisfy all the boundary conditions. In such cases a linear combination of TE and TM waves which may satisfy the boundary conditions are used. Such waves are called hybrid waves.

The case where the dielectric entirely fills the waveguide is not realistic but the essential features of the interaction process can be displayed in this simplest model. Consider a wave propagating along the z-direction which is the axis of the cylinder. For phase variations as $\exp[-i(\omega t-k_z z)]$, the longitudinal component of the field E_z turns out to be

$$E_z = A\, J_o\, (k_1\, r) \tag{4}$$

where $k_1^2 = (\omega^2\, \varepsilon/c^2 - k_z^2)$. Boundary condition at $r = b$, demands $J_o(k_1 b)=o$. This gives

$k_1 b = x_n$, x_n is the n-th root of $J_o(k_1 b) = o$

i.e.

$$(\omega^2 \varepsilon / c^2) - k_z^2 = x_n^2/b^2 \tag{5}$$

This gives the dispersion relation for a fully dielectric loaded waveguide. For a dielectric free metallic hollow cylinder, the dispersion relation is same as Eq.(5) with $\varepsilon=1$. For the most simplest case of a wave travelling through an infinite dielectric medium, the dispersion relation is

$$\omega^2 = k_z^2\, c^2/\varepsilon \tag{6}$$

The dispersion characteristics have the general form shown as in Fig. (4).

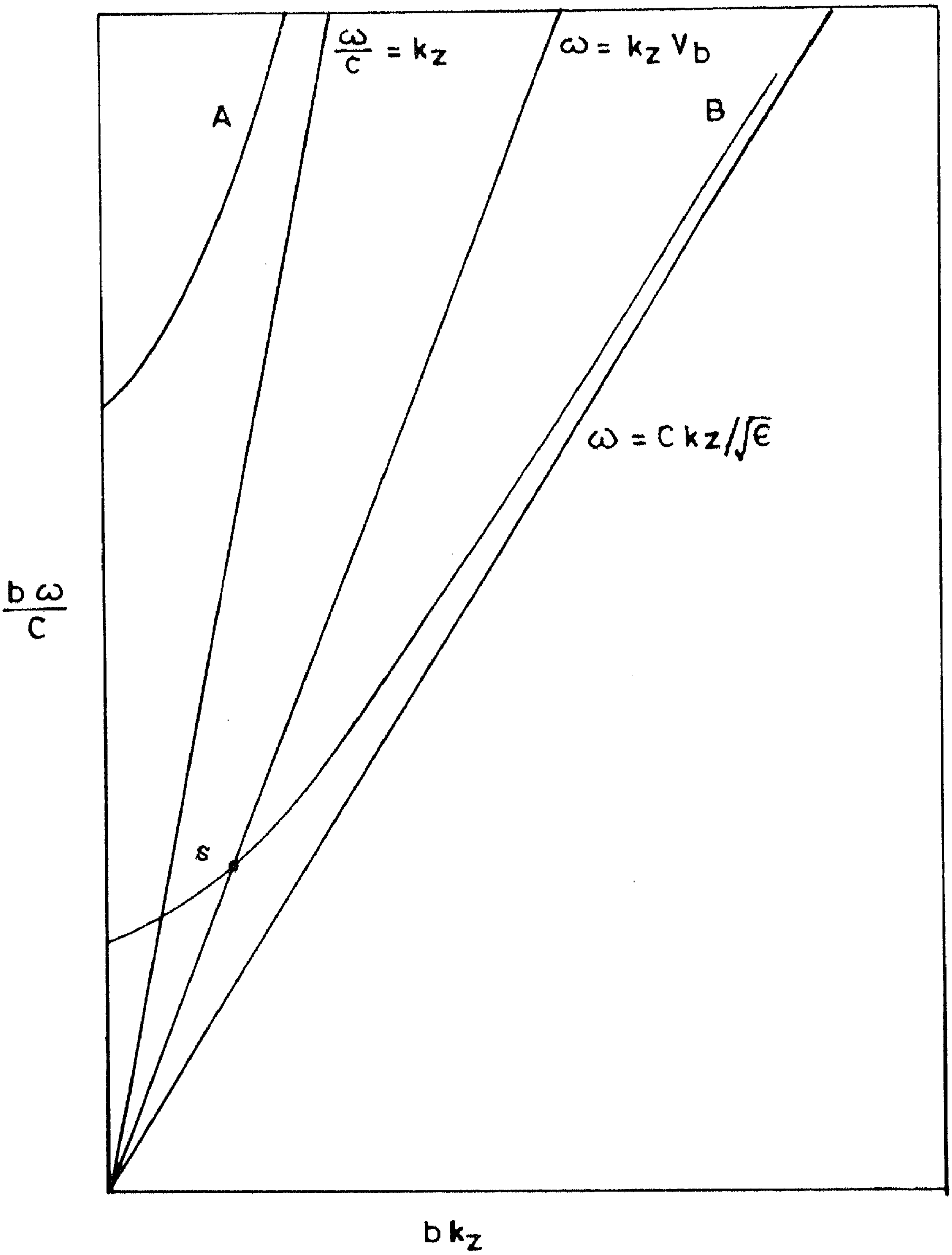


Fig. 4

Dispersion characteristics of a dielectric filled Cerenkov free electron laser

The curve 'A' is the dispersion curve for a hollow metallic waveguide without dielectric. The phase velocity along the curve is greater than unity. At large wave numbers, the curve approaches asymptotically to the light line ($\omega=k_zc$). A beam cannot propagate in this region, consequently no radiation occurs in this case. The curve'B' represents the dispersion behaviour of the dielectric filled guide (Eq.(5)). Near the cut off, the phase velocity of the mode is greater than unity however if one moves to higher axial wave numbersthe phase velocity of the mode slows down and the curve asymptotically approaches to the dielectric line ($\omega= k_zc/\sqrt{\varepsilon}$) (Eq.(6)). The $\omega= k_zV_b$ represents the beam mode. The frequency as well as the radiation wavelength is determined by the synchronism (Point S) of the beam and the mode dispersion curve of the waveguide.

In this present thesis, we study the interaction region physics of a cerenkov free electron laser employing analytical and numerical techniques. The issues of finite velocity spread of the electron beam, excitation of TE modes, operation of a cerenkov free electron laser in an explosive mode, effect of self beam rotation have been the focal point of our investigations. Plasma effects and efficiency enhancement in a tapered cerenkov free electron laser have been addressed subsequently. We have also studied some nonlinear effects arising through the interaction of the laser radiation with plasma. The thesis has been organized in the following manner.

In first chapter, we study the finite transverse velocity ($V_\perp$) effect of an annular electron beam on cerenkov free electron laser instability. The introduction of a finite $V_\perp$ of the beam leads to the possibility of excitation of TE modes. We have developed a rigorous kinetic theory of this process in a cylindrical waveguide taking an annular electron beam. The instability appear via cerenkov and cyclotron resonance interactions. The growth rate increases with $V_\perp$.

In Chapter II, we examine the possibility of excitation of TE modes in a partially dielectric lined waveguide via second harmonic generation of the beam space charge. It requires the resonance condition, $2\omega-2k_z V_b=-\omega_b\gamma^{-3/2}$. The second harmonic of the TE mode drives density oscillations which are in resonance with the beam. The density oscillations couple with the TE mode to produce a nonlinear current driving the TE mode. The TE mode and the longitudinal second harmonic wave amplitudes grow explosively on a time scale which is inversly proportional to the square root of the normalised wave amplitude.

In chapter III, we investigate the effect of beam self rotation on Cerenkov free electron laser instability. At large beam currents, the beam space charge produces a radial electric field causing $\vec{E} \times \vec{B}$ rotation of the beam. Beam rotation modifies the eigen frequencies of the beam mode by $\ell\, \omega_\alpha/\gamma$ leading to generation of synchronous frequencies shifted by $\ell\omega_\alpha/\gamma$ where ℓ is the azimuthal harmonic mode number, ω_α is the angular frequency of rotation, γ is the beam energy.

In chapter IV, we have examined the possibility of efficiency enhancement by tapering the thickness of the dielectric lining in a cerenkov free electron laser. The efficiency enhancement is due to the forced slowing down of the waveguide mode to compensate over the beam energy loss. Numerical analysis and results are presented for TM_{01} mode of a waveguide in a cylindrical geometry.

In chapter V, we study plasma effects on a cerenkov free electron laser. Allowing plasma inside dielectric lined waveguide helps in transporting higher beam currents via beam space charge and current neutralisation. If the plasma densiy is kept low, it may not strongly affect the electrodynamics of the resonator. At frequences less than the electron cyclotron frequency, plasma has a refractive index greater than unity hence at such frequencies one can remove the dielectric lining and the plasma itself can act as a slowing down medium.

In chapter VI, we study two important nonlinear effects arising through the interaction of high power cerenkov free electron laser radiation with plasma.

(i) Filamentation instability

It is an important nonlinear process in the interaction of laser radiation with plasma. It leads to breaking of the beam into small filamentary structures. The existing theories of filamentation instability are restricted to homogeneous plasmas. Here we study the effect of an axial density gradient on the filamentation of the beam. It is found that the inhomogeneity of plasma leads to a much stronger spatial growth of the filamentation instability. The growth rate decreases with the transverse wave vector of the perturbation. Thus the shorter wavelength perturbations tend to grow faster.

(ii) Three-half harmonic emission from a laser filament:

High power cerenkov free electron lasers are likely to undergo Two Plasmon Decay in the filamentary structures through the filamentation instability. The process is important near quarter critical density layer and is responsible for generation of plasma waves of frequency at $3\omega/2$ observed in many experiments. Here we study three-half harmonic emissions from a self trapped laser filament arising through a nonlinear interaction of the pump wave with the density oscillations at the langmuir frequency. The emitted power is calculated for the backscattered wave. It is seen to decrease with the increasing size of the laser filament.

The work mentioned above has been published/communicated in the form of the following manuscripts.

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5) Three-half harmonic emission from a laser filament in a plasma channel, G.Mishra, I. Talukdar, Vijaysree & V.K. Tripathi, IEEE Trans. on Plasma Sc. (In press, 1989).

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7) Plasma effects in cerenkov free electron laser, G.Mishra & V.K.Tripathi; J. Appl. Phys. (Communicated, 1989).

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