1. INTRODUCTION

Static magnetic fields that have a periodic space variation are commonly used in free electron lasers. These static, periodic magnetic fields are often referred to as wiggler fields or pump fields. A simplified diagram of a free electron laser is shown in figure 1.1.

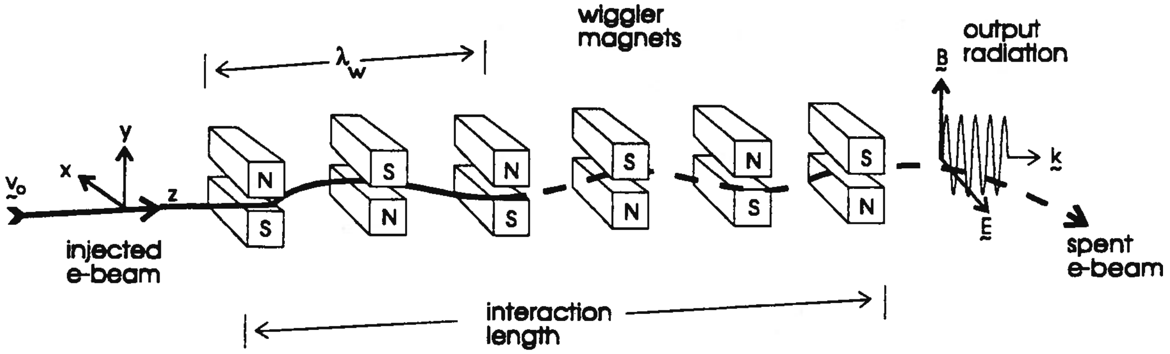

Figure 1.1 Diagram of a typical free electron laser configuration [1].

This diagram shows a linearly polarized wiggler field created by a series of periodically spaced permanent magnets. As the electron passes through the wiggler field, with a velocity **v**, it is forced to oscillate due to the **v** x **B** forces. A radiating field is created by the oscillations of the electrons. The amplitude and frequency of the resulting field can be altered by modifying the strength and period of the permanent magnets.

In addition to linearly polarized wiggler fields, helical wiggler fields are also commonly used in free electron lasers. Helical wiggler fields are usually created by a bifilar coil winding where the period of the wiggler is dependent on the tightness of the coil windings. The current traveling through the coils gives rise to a magnetic field that rotates around the axis of the electron beam.

Helical wiggler fields can also be created by permanent magnets. This is shown in figure 1.2.

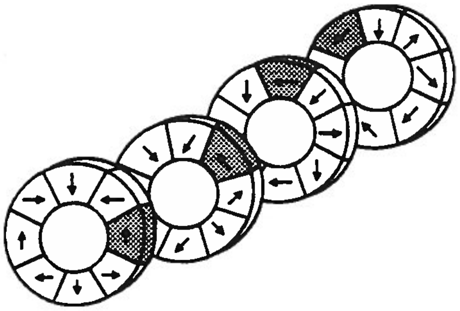

Figure 1.2 Helical magnetic wiggler structure [2]

An individual ring is created by magnetizing a ring, cutting it into pieces, then rearranging the pieces. Successive rings in the structure are rotated a set number of degrees to generate the helical field. The period of the field is determined by the distance between two rings in the structure having the same orientation. Although there are many different types of setups, the primary purpose of the wiggler structure in a free electron laser is to create a magnetic field perpendicular to the direction of the electron beam.

The concept behind the free electron laser is relatively new. Marshall [3] writes that the idea originated in 1933 with a paper by Kapitza and Dirac, and that Motz performed some of the first experiments in the 1950's. During the 1970's, experimentation branched into different areas with Stanford, Columbia, and Cornell Universities and the Naval Research Laboratory performing research that has led to the current free electron laser design [4] . The theory, design, and fabrication of free electron lasers continues to grow. There are now numerous publications, laboratories and professional societies dealing with free electron lasers.

Free electron lasers can be used as amplifiers or as oscillators [4]. When used as an amplifier, a signal is inserted along with the electron beam and is amplified as it passes through the wiggler field. As an oscillator, the electron beam is confined between two mirrors. During successive passes through the wiggler the spontaneous radiation is amplified. Free electron lasers can be operated in frequency ranges from around 3×10^{9} to 3×10^{15} Hz or in terms of wavelength from 10^{-5} to 10 cm. Peak power levels range from 10^{3} to 10^{9} watts with the larger output powers being achievable at the lower frequencies.

Free electron lasers have an advantage over conventional lasers in that they are tunable over wide bandwidths. In a conventional laser the emission frequency is determined by the oscillations of electrons bound to atoms. Since the electrons are bound, they can generally be forced to oscillate only at specific frequencies [5]. In free electron lasers, the electrons are not bound to atoms, hence the word "free". Since the electrons are not bound they can be forced to oscillate over wider frequency ranges. The oscillation frequencies are not completely determined by the wiggler field but can also be altered by controlling the energy level of the electron beam. Most free electron lasers can be operated over a range of electron energy exceeding a factor of two, which corresponds to more than a factor of four for wavelength [5]. In addition to the wide bandwidth, the gain can be scaled to very high levels much more easily than conventional lasers. This is due to the fact that the heat buildup in the free electron laser is associated with the energy of the electrons which are traveling at relativistic speeds thereby making it easier to dissipate the heat. High power conventional lasers generally dissipate heat by flowing the laser medium, which is usually a gas, out of the laser. This can only be done at speeds which are slow compared to relativistic speeds.

A disadvantage of free electron lasers is that since the wavelength of the output wave is dependent on so many physical parameters of the device, it generally cannot be tuned as a frequency standard. In conventional lasers, the wavelength depends on a fixed, internal transition within an atom making it a very stable source [3]. Another disadvantage of free electron lasers is that they tend to be large and are typically very expensive, with most facilities costing several million dollars. Much effort now is geared to developing applications to justify the costs of developing and maintaining these facilities. Brau [5] discusses many applications for the free electron laser ranging from research in other sciences to medicine, industrial processing and strategic defense.

The heart of the free electron laser is the wiggler field. Referring again to figure 1.1, we can write an approximation to the wiggler magnetic field created by the periodically spaced permanent magnets.

$$\overrightarrow{B_w} = \hat{y} B_{wo} \sin(k_w z) \tag{1.1}$$

Taking the curl of (1.1) gives us

$$\overrightarrow{\nabla} \times \overrightarrow{B_w} = -\hat{x} B_{wo} \sin(k_w z)\, k_w \tag{1.2}$$

This expression does not satisfy Maxwell's equation $\overrightarrow{\nabla} \times \overrightarrow{B} = 0$. Marshall [3] discusses this issue and mentions that there is also a small component of the magnetic field in the z direction, and that we have not accounted for a dependence of the field on the x and y coordinates. Marshall states that the amplitudes of the electron oscillations should be kept small compared with the scale length of the wiggler field, k_w^{-1}, in order for equation (1.2) to be valid.

Given the magnitude and period of the wiggler field we can write an expression for the wavelength of the emitted wave.

$$\lambda_l = \frac{\lambda_w}{2\gamma^2}\left[1 + \frac{K_w^2}{2}\right] \tag{1.3}$$

where

$$K_w = \frac{eB_w\lambda_w}{2\pi mc} \tag{1.4}$$

is referred to as the strength parameter [4], where e is the absolute value of the charge of an electron, m is the mass of an electron and c is the speed of light. As can be seen by equation (1.4), the strength parameter is strongly influenced by the amplitude and wavelength of the wiggler field. The device used to produce the wiggler field is sometimes referred to as an undulator. The differentiation is generally made by examining the strength parameter. If the strength parameter is one or less, the device is called an undulator. If the strength parameter is much greater than one, the device is called a wiggler [3]. Winick [6] refers to the difference by defining an undulator as having many periods and a wiggler having few periods.

The term, γ, in equation (1.3) is the energy of an electron expressed in terms of its rest energy and as given by

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1.5}$$

where v is the velocity of the electrons in the free electron laser. Brau [5] gives typical values for a linearly polarized wiggler as $B_w = 0.5\,\mathrm{T}$, $\lambda_w = 2\,\mathrm{cm}$, $\gamma = 200$, and the length of the wiggler structure to be two meters which gives 100 periods. This yields a free electron laser wavelength of 0.5 µm or a frequency of 600 THz. Other values and parameters can be found in the descriptions of free electron laser facilities found in the proceedings of the eleventh conference on free electron lasers [7].

The power of the free electron laser is dependent on the mechanism by which the radiation from each electron becomes coherent. This mechanism, is referred to as the ponderomotive wave or as a pump wave. It involves a bunching of groups of electrons, where the bunching frequency is on the same order of the source wave frequency being amplified. This occurs when there is a resonance condition between the period of the wiggler and the period of the output frequency which can be developed from equation (1.3). Basically the electrons will gain or loose energy thereby causing them to speed up or slow down. This brings the oscillations in phase where the power is determined by the number of electrons in the beam.

The above discussion describes the importance of the wiggler field to the performance of the free electron laser. Unfortunately, once a permanent wiggler magnet structure is created for a free electron laser it is usually difficult to modify it. It is shown, using a theoretical model, that the sudden creation of a plasma medium in the presence of an electromagnetic wave (source wave) results in the generation of a controllable wiggler magnetic field and a controllable wiggler electric field. This effect is studied in the presence of a fixed linearly polarized wiggler field and later extended to a helical wiggler field. The damping rates of the wigglers in a lossy plasma are examined. The application of these wiggler fields for use in a free electron laser is also discussed.