The Design of a Millimeter Wave Waveguide FEL Experiment*

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Abstract

A millimeter wave waveguide FEL project is under design at UCLA. In a waveguide FEL, the group velocity can be controlled by changing its waveguide dimensions. This feature provides the opportunities to study the FEL physics in different conditions, in particular near the zero slippage regime. The first phase will use the beam from the photo-injector and operate at a wavelength longer than the electron beam bunch length. Since the electron beam is pre-bunched, we expect a radiation intensity proportional to the square of the electron density. The second phase will use the beam from the rf linac with adjustable beam energy from 5 to 15 MeV. The FEL wavelength will be about 1 millimeter. The superradiance and the self amplified spontaneous emission (SASE) will be studied. In this paper, we present the design parameters and some numerical results.

I. Introduction

Theoretical studies of the free electron laser (FELs) in the high gain regime have shown that with an appropriate selection of the operation conditions, the electron density, beam bunch length, and the wiggler length, the radiation field and the electron bunching can undergo exponential growth as a result of a collective instability of the electron beam-wiggler-radiation field system[1] . Furthermore, it is found theoretically and demonstrated numerically that the superradiance, a new dynamical regime of cooperative spontaneous emission of synchrotron radiation, in which the radiation field is proportional to the square of the electron beam peak current, can emerge under certain conditions[2-4] . One of the critical requirement for operation in the superradiance regime is that a very long wiggler is needed, which can not be satisfied for most experimental projects. Up to now, no experiments have investigated these superradiant regimes.

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Although it is indispensable for the operation of a millimeter wavelength FEL, the use of a waveguide also provides the flexibility to easily control the phase velocity and the group velocity of the radiation field by changing the height of the guide. This unique feature makes it possible to control the slippage length, which is proportional to the difference between the electron longitudinal velocity and the group velocity of the radiation field. Therefore, the conditions for the superradiance to occur could be satisfied in a waveguide FEL even using a 'short' wiggler and a short electron beam bunch. To observe these high gain FEL dynamical regimes is one of the goals of our millimeter wavelength FEL experiment project.

In this FEL experiment, we intend to cover the wavelength ranging from 3 mm down to 0.5 mm, using a single wiggler and adjusting the electron beam energy from 3 MeV to 15 MeV. The operation regime will be concentrated around zero slippage. In this paper, our rf linac system and the electron beam parameters are described. The characteristics of a waveguide FEL for different dynamic regimes are briefly reviewed. We then discuss the design of the wiggler, and conclude the paper by a summary of the parameters of the waveguide FEL calculated from a 1-D model.

II. The Linac System and the Beam Parameters

The rf linac system at UCLA, shown schematically in Fig.1, is dedicated to FEL experiments and to the study of plasma focusing and wake field acceleration[5] . This system consists of a laser-illuminated photo-cathode injector and a compact rf linac. The RF power is supplied from a single 25 MW SLAC-type klystron with a rf pulse width of about 3 μs. A solenoid is used to focuse the beam after it exits from the rf gun.

The rf gun consists of one and a half cells operating at π-mode with resonance frequency at 2856 MHz. Photoemission is initiated by illuminating the cathode with a frequency quadrupled light pulse from a Nd:YAG/Glass laser. Two sapphire view-ports are oriented 70° from the electron beam axis and situated symmetrically about the line perpendicular to the planar cathode's surface. For the time being, a copper cathode is used. In the test of the rf gun, a quantum efficiency of 10^{-4} has been achieved. Electron charge of more than 1 nC with a bunch length of about 4 ps has been observed experimentally[6] . These preliminary experimental results have demonstrated that the injector can produce a high brightness electron beam with a peak current up to 200 ampere with beam energy up to 4.5 MeV. Some of the recent experimental results are shown in Table I.

The rf linac is a prototype of the plane-wave transformer (PWT) structure designed by Swenson[7] . It consists of eight cells with a total length less than half a meter[8] , as shown scematically in Fig.2. The disk-washer array is separated from the cylindric tank with the array acting as a "center conductor" to support a TEM-like plane-wave traveling back and forth along the structure and transforming the transverse field of the plane-wave into a longitudinal electric field for the acceleration. Unlike the conventional rf linac structure, the PWT is operated at TM_{02}-like mode instead of the fundamental mode. Fig.3 shows the field pattern from the 3-D code MAFIA[9] . Some electrical parameters are shown in Table II. We see that the PWT has a high impedance and high unloaded Q-value. Because the rf power fed into it is adjustable, the PWT can achieve an electron energy gain up to 12 MeV.

III. Characteristics of the Waveguide FEL

In a waveguide, the frequency f and the wave number k of the nth mode is related by the dispersion relation[10] :

$$k^2 = \frac{\omega^2}{c^2} - k_{cn}^2 \tag{1}$$

where k_{cn} is the cut-off wave number. The group velocity of the electromagnetic wave in the waveguide is given by:

$$v_g = c\sqrt{1 - (\frac{\lambda}{\lambda_{cn}})^2} \tag{2}$$

where λ_{cn} is the cut-off wavelength of the nth mode. For a rectangular waveguide with a height b and operating at the TM_{01} mode, $\lambda_{c01} = 2b$. In terms of the wiggler wave-vector $k_w = 2\pi/\lambda_w$, with λ_w being the wiggler period, the resonance condition in FEL can be written as follows:

$$\beta_z = \frac{c}{\omega}(k + k_w) \tag{3}$$

By definition and using the Eqs.(2) and (3), the slippage length for a waveguide FEL becomes:

$$l_s = (v_g - v_z)L_w/v_z = N_w\lambda_g(\frac{1-X}{1+\xi}) \tag{4}$$

where L_w is the total length of the wiggler, N_w, its period number, $\xi = \lambda_g/\lambda_w$, with λ_g being the waveguide wavelength and the dimensionless waveguide parameter X is defined by:

$$X = \frac{\lambda_g\lambda_w}{\lambda_c^2} \tag{5}$$

Besides the slippage length, another parameter to distinguish the different regimes is the cooperative length, $\overline{l_c}$, which is defined by the ratio of the radiation wavelength to the gain length per wiggler. Taking the waveguide into account, it is found:

$$\overline{l_c} = l_c\frac{1-X}{(1-\frac{X}{2})^{5/6}(k_0/k)^{1/3}} \tag{6}$$

where $l_c = \frac{\lambda}{4\pi\rho}$, the cooperative length for FEL ignoring the waveguide effect. We see from Eqs.(4) and (5) that both the slippage parameter and cooperative length are modified by the parameter X.

It has been shown that if slippage is taken into account, there exist two different regimes in the high gain FEL, which are defined as long-bunch or short-bunch regimes with respect to the cooperative length[2,3] . In the short-bunch regime, the radiation emitted by the electrons has to escape from the bunch in a time shorter than the synchrotron period so that the re-absorption of the radiation by electrons can not happen. This requires that the slippage length is much longer than the bunch length and the cooperative length is slightly larger than the bunch length. In a waveguide

FEL, this condition could be satisfied by choosing an over-sized waveguide so that $X << 1$. In the long-bunch regime, the steady-state operation requires that the bunch length is very long comparing the slippage distance. However, the slippage distance can be suppressed in a waveguide FEL by choosing the waveguide height b so that $X = 1$. Thus the condition for this regime can be easily satisfied. We can also choose an intermediate dimension b so that $0 < X < 1$. In this way, the slippage length can be reduced but is still larger than the bunch length. Thus, the tailing effect, or the strong superradiance would be observed. Therefore, it is possible to observe the three regimes in this project although we use a short bunch electron beam and medium long wiggler.

IV. The Design of the Wiggler

We intend to use one single wiggler to cover a wide range of FEL wavelength. To this end, we prefer to build a wiggler with an adjustable magnetic field, while its period length is fixed. For a rectangular waveguide working on the TE_{01} mode, the zero slippage condition requires that the waveguide height b satisfy the following relation:

$$b = 2\sqrt{\frac{1}{\beta_z}\lambda\lambda_w} \tag{7}$$

and the peak magnetic field has to be:

$$B_w = \frac{1.514}{\lambda_w}\sqrt{\frac{\beta_z\gamma^2\lambda}{\lambda_w} - 1} \tag{8}$$

Both equations show that a longer wiggler period length is preferable, as long as $\lambda_w \leq \beta_z\gamma^2\lambda$ is not violated. Out of practical considerations, we choose a period length of 10 centimeter for the wiggler.

In order to observe different FEL dynamical regimes, the wiggler should provide an adjustable peak field up to 3 kilo-gauss. Thus, we intend to design an electromagnetic planar wiggler. For the sake of simplicity, we consider a similar design to the micro-wiggler at BNL[11] . The cross-section and magnetic field lines of the wiggler, calculated by the 2-D program POISSON[12] , is shown in Fig.4. The unsaturated magnetic field is about 4.4 kilo-gauss for a gap of 1.4 centimeter with a current of 5000 ampere turns.

To transport a high peak current beam (200 Ampere) through a long wiggler, it is necessary to provide electron focusing in both planes. Planar wigglers have natural focusing only in the vertical plane. It is well known that the parabolic pole shaping can provide focusing in the wiggle plane[13] . However, this scheme provides a weak, or constant focusing. It was found from numerical simulation that the high gain FEL can benefit from a strong quadrupole focusing[14] . A scheme to achieve quadrupole focusing is to alternatively tilt the poles of the wiggler, as shown schematically in Fig.5. We use a 3-D computer program TOSCA[15] to calculate the magnetic field. Fig. 6 shows the variations of the B_x vs. y and B_y vs. x at different position along the beam axis. To the first order, both components have a linear dependence on transverse coordinates respectively. The theoretical and numerical analysis of the focusing properties for the wiggler are being studied.

IV. Summary

This experiment will be carried out step by step. The first phase will work on 3 *mm* wavelength and low energy electron beam. For this FEL wavelength and an electron bunch length of about 5 ps, the beam is prebunched. Thus we would expect a superradiant regime with the radiation power being proportional to the square of the peak current. Fig.9 shows the numerical results with the electron parameters from the Table I. The magnetic field on axis is 2.1 kilo-gauss. The electron beam energy is 5 MeV. It is found that an output power larger than 10 MW can be produced, with a saturation length of about 4.5 meter ($N_w = 45$) and an input power of 1 kW.

The second stage of this project will work on a shorter wavelength. For the FEL wavelength of one millimeter, we will use a higher energy beam to reduce the saturation length. We will work on both the steady-state and the strong superradiance regimes. Some related parameters are listed in Table III, which are calculated from the 1-D model. As for the half millimeter wavelength, there are some practical difficulties to work in the steady-state regime due to the requirement of small waveguide dimensions. However, we can work on the weak superradiance regime because larger waveguide dimensions are necessary to reduce the waveguide parameters.

Some important experimental issues, such as the coupling and the detection of the radiation, the synchronization of the input laser pulse with the electron beam, are being studied. More sophisticated numerical simulations for the shorter wavelength and the superradiance regimes are underway. We believe that much novel FEL physics can be studied in this project. To fully understand these mechanism will be crucial to the future FEL development.

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