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Section A

A millimeter wave FEL driven by a photocathode rf linac *

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We present the design of a millimeter wave FEL based on the UCLA photocathode rf linac. The linac energy can be varied between 5 and 18 MeV. The electron pulse duration is 2 ps FWHM, with a peak current exceeding 150 A. The FEL is designed to operate in the high gain Compton regime, controlling the slippage with the propagating radiation in a waveguide. The design will permit the exploration of the basic FEL physics in this regime, including the exploration of saturation and lethargy in the superradiant and steady state regime.

1. Introduction

Theoretical studies of the free electron laser (FEL) in the high gain regime have shown that with an appropriate selection of the electron density, the 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 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 [2,3]. One of the critical requirements for operation in the superradiant regime is that a very long wiggler is needed, which is usually not satisfied for most FEL projects. No physical experiments have investigated these superradiant regimes yet.

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 group velocity of the radiation field by changing the dimensions of the waveguide. 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 an FEL with a waveguide even using a "short" wiggler and a short electron bunch. To observe these high gain FEL dynamical regimes is one of the goals of our millimeter wave FEL experiment.

In this FEL experiment, we intend to cover the wavelength ranging from 3 down to 0.5 mm, using a single wiggler and adjusting the beam energy from 3 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 FEL with a waveguide are briefly reviewed. Then a design of the wiggler is discussed. The FEL parameters estimated from a 1-D model are presented.

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2. The photocathode rf linac system

The rf linac system at UCLA is dedicated to FEL experiments, the study of plasma focusing and wake field acceleration [4]. This system consists of a laser-illuminated photocathode injector and a compact rf linac, which share a single 25 MW SLAC-type klystron (S band).

The rf gun consists of one and a half cells operating at π-mode. Photoemission is initiated by illuminating the cathode with a frequency quadrupled light pulse (266 nm) from a Nd:YAG/glass laser. Two sapphire viewports 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. The solenoid at the gun exit is used to reduce the divergence of the beam. In the commissioning test of the rf gun, a quantum efficiency of 10^{-4} has been achieved. Electron charge of more

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Table 1
Experimental results of the rf gun

Charge per bunch	1 nC
Bunch length (rms)	5 ps
Beam energy	4.5 MeV
Emittance ϵ_{nx}	10π mm mrad
Energy spread	0.5%
Peak current	200 A

than 1 nC with a bunch length of about 4 ps has been observed experimentally [5]. These preliminary experimental results, as shown in Table 1, have demonstrated that the injector can produce a high brightness electron beam with a peak current exceeding 150 A with a beam energy up to 4.5 MeV.

The rf linac is a prototype of the plane-wave transformer (PWT) structure designed by Swenson [6]. It consists of eight cells with a total length of less than half a meter [7]. 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, the PWT is operated at the TM_{02}-like mode instead of the TM_{01}-like one. The unloaded Q and the impedance of the PWT, calculated from the 3-D code MAFIA [8], are about 30 K and 130 MΩ/m respectively. The PWT has advantages of high acceleration gradient, low cost and easy manufacture. The electron energy gain from the PWT linac can reach up to 14 MeV.

3. Characteristics of the FEL with a waveguide

There are two dynamical regimes in the high gain FEL: the steady state and the superradiance. Strictly speaking, the steady state is a regime without slippage between the electron beam and the radiation. The superradiant regime can be further divided in long-bunch or short-bunch regimes with respect to the cooperation length [2,3]. In the short-bunch regime, the radiation emitted by electrons escapes from the bunch in a time shorter than the synchrotron period so that the re-absorption of the radiation by electrons cannot happen. This means that the slippage length is much longer than the bunch length and the cooperation length is slightly larger than the bunch length. In the long bunch regime, there is a trailing region of the pulse, which evolves as a short pulse. If the electron bunch is sufficiently long, the radiation does not escape from the pulse but build up to exhibit spiking of the intensity after saturation of the steady state signal in the leading region of the pulse. Therefore the superradiant regime needs a long wiggler, which makes it difficult to be tested for a short wavelength FEL. However, it becomes possible to test the theory in a millimeter wave FEL due to the use of a waveguide.

For an FEL operating in the millimeter range, a waveguide is necessary in order to confine the radiation. As is well known, the group velocity of the electromagnetic wave in a waveguide is less than the speed of light and is varied with dimensions of a waveguide. Because of the dispersion in a waveguide, some FEL characteristic parameters are also modified. One is the slippage length, which can be expressed as follows [9]:

$$l_s = (v_g - v_z)\frac{N_w \lambda_w}{v_z} = N_w \lambda_g \left(\frac{1 - X}{1 + (\lambda_g/\lambda_w)} \right), \qquad (1)$$

where v_g is the group velocity of the radiation, v_z is the longitudinal velocity of the electrons, λ_g is the waveguide wavelength, λ_w and N_w are the period length and the period number of the wiggler respectively, and X is the dimensionless waveguide parameter, which is defined as follows:

$$X = \lambda_g \lambda_w / \lambda_c^2 \qquad (2)$$

where λ_c is the cutoff wavelength. Another parameter is the cooperation length, $\bar{l}_c$, which is defined by the ratio of the radiation wavelength to the gain length per wiggler. For the FEL with a waveguide, it becomes [9]:

$$\bar{l}_c = l_c \frac{1 - X}{(1 - X/2)^{5/6} (k_0/k)^{1/3}}, \qquad (3)$$

where $l_c = \lambda/(4\pi\rho)$ is the cooperation length for an FEL ignoring the waveguide effect. ρ is the fundamental FEL parameter [1].

We see from Eqs. (1) and (3) that both the slippage parameter and the cooperation length are modified by the waveguide parameter X. Therefore, by adjusting the waveguide dimensions, the conditions for different high gain regimes can be satisfied. For the steady-state regime, we choose a waveguide so that the group velocity is exactly equal to the beam velocity, that is $X = 1$. For the short bunch regime, we can choose an oversized waveguide so that $X \ll 1$. For the long-bunch regime, we can also choose an intermediate waveguide dimension so that $0 < X < 1$. In this way, the slippage length can be reduced but is still larger than the bunch length. Thus, as long as the gain is sufficiently high, it is possible to observe the three regimes in this project although we use a short electron bunch and a medium long wiggler.

4. The design parameters 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. The peak magnetic field on axis, for a linearly polarized wiggler, can be found from the zero slippage condition (B_w in T, λ_w in cm):

$$B_w = \frac{1.514}{\lambda_w}\sqrt{\frac{\beta_z\gamma^2\lambda}{\lambda_w} - 1}. \quad (4)$$

It shows that a longer wiggler period length is preferable, as long as $\lambda_w \le \beta_z\gamma^2\lambda$ is not violated. We choose a period length of 10 cm for the wiggler.

In order to observe different FEL dynamical regimes, the wiggler should provide an adjustable peak field up to 3 kG. Thus, we intend to design an electromagnetic wiggler. For the sake of simplicity, we consider a design similar to the micro-wiggler at BNL [10]. The unsaturated magnetic field is, calculated using POISSON [11], about 4.4 kG for a gap of 1.4 cm with a current of 5000 A-turns.

To transport a high peak current beam (exceeding 150 A) 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 [12]. 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 [13]. A scheme to achieve quadrupole focusing is to alternatively tilt the poles of the wiggler, as shown schematically in Fig. 1. To the first order, both components B_x and B_y, calculated using TOSCA [14], have a linear dependence on transverse coordinates y and x respectively. The theoretical and numerical analysis of the focusing properties for the wiggler are being studied.

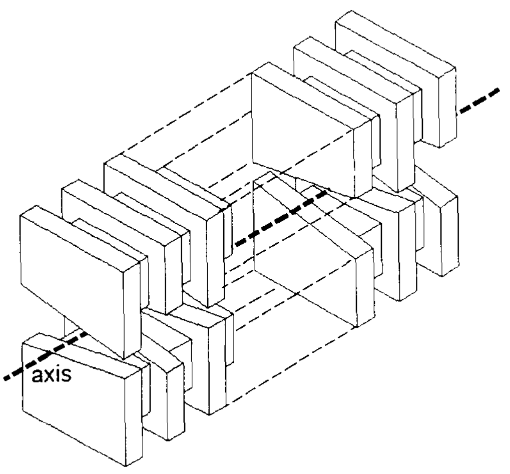

Fig. 1. The electromagnetic wiggler schematics.

5. FEL parameters from a 1-D model

One advantage of this experiment is the high quality and high current beam with a wide range of beam energy adjustment. The first phase of this project will work on a 3 mm wavelength. The beam energy will vary from 5 to 10 MeV, depending on the waveguide dimensions. For this FEL wavelength and a 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 beam current.

In order to estimate the FEL performance of a prebunched beam, we follow the analysis of refs. [9,15]. By linearizing the FEL working equations, the Laplace transformed amplitude of the radiation wave, neglecting the velocity modulation, is found to be:

$$X(s) = \left[X_0(s^2+\sigma) + F_0(s + i\rho\sigma)\right]/\Delta(s), \quad (5)$$

where X_0 is the input signal and F_0 is a phase prebunching factor. These parameters are defined as follows:

$$\rho = \frac{1}{\gamma_r}\left(\frac{a_w}{4}\frac{\omega_p}{ck_w}\right)^{2/3}, \qquad \sigma = 4\rho\frac{1+a_w^2}{a_w^2},$$

$$\delta = \frac{1}{2\rho}\frac{\gamma_0^2-\gamma_r^2}{\gamma_r^2}, \qquad F_0 = \frac{1}{N_e}\sum_{l=1}^{N_e}\exp(-i\theta_{l0}),$$

$$\Delta(s) = s\left[s^2 - i\left(\delta - \frac{\sigma}{2}\right)s - (2\rho+\sigma)\right] - i\left[1 - \sigma\left(\delta - \frac{\sigma}{2}\right) - \sigma\rho^2\right]. \quad (6)$$

If we write the roots of Eq. (6) as s_j, one gets a general expression of the amplitude of the radiation:

$$A(\bar{z}) = \sum_{j=1}^{3}(x_j + f_j)\exp(s_j\bar{z}), \quad (7)$$

where x_j, and f_j are the residues of the terms in Eq. (5) and $\bar{z} = 2k_w\rho z$ is a normalized distance. Therefore, the power output is found to be:

$$P_o(\bar{z}) = P_s(1+G_0) + \rho P_b|F_0|^2 G_b + \sqrt{P_s\rho P_b}\,|F_0|G_{sb}, \quad (8)$$

where P_s is the external input power and $P_b = A_e\beta_z cn\gamma_r mc^2$ is the resonant electron beam power. G_0 is the conventional output for a uniform beam, while other terms are due to the electron prebunching. For the Compton regime, one can simplify these equations by going to the limit $\rho \to 0$. In this case, the output power turns to be:

$$P_0(\bar{z}) = P_s\left[1 + \frac{4}{\delta^3}\left(1 - \cos(\delta\bar{z}) - \frac{\delta\bar{z}}{2}\sin(\delta\bar{z})\right)\right] + \rho P_b|F_0|^2\left(\frac{\bar{z}^2}{2}\right)\frac{\sin^2(\delta\bar{z}/2)}{(\delta\bar{z}/2)^2} - \sqrt{P_s\rho P_b}\,|F_0|\left(\frac{2}{\delta}\right)[1 - \cos(\delta\bar{z})]. \quad (9)$$

In most of cases, we have to reckon on numerical methods to find the roots of Eq. (6), then rationalize Eq. (5) and do the reverse Laplace transformation. In this way, we can estimate the power as well as the bunching factor.

We also used a 3-D program to estimate the output power and saturation length. Fig. 2 shows the result with the electron parameters from the Table 1. The magnetic field on axis is 2.1 kG. 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 m ($N_w = 45$) and an input power of 1 kW.

The second stage of this project will work on a wavelength of 1 mm or shorter. For these shorter wavelength FEL experiments, the beam energy will be raised to above 10 MeV. Both the steady-state and the superradiant regimes are going to be tested. These FEL parameters for the steady-state regime are listed in Table 2, which are calculated from a 1-D model [9]. 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.

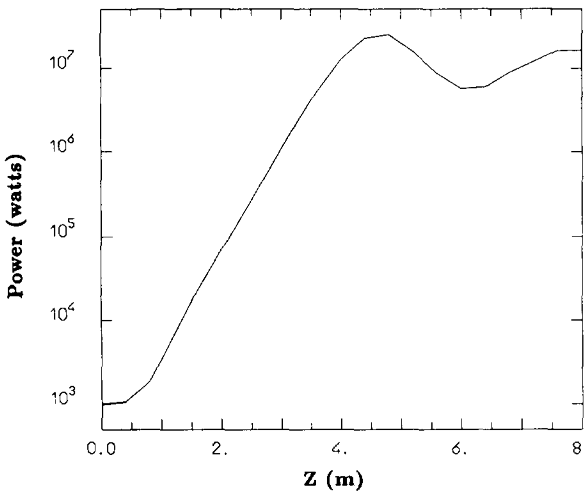

Fig. 2. The radiation output power along the wiggler (input power: 1 kW, peak magnetic field: 2.1 kG; beam current: > 150 A).

Table 2
FEL parameters calculated from a 1-D model [a]

Parameters	3 mm	1.07 mm	0.5 mm
Beam energy γ	10	17	25
Wiggler field (kG)	2.12	2.18	2.2
Period number	45	50	55
Waveguide height (mm)	8.7	5.2	3.5
FEL parameter ρ	0.028	0.023	0.021
Gain length (m)	0.58	0.68	0.77
Saturation length (m)	4.0	4.7	5.2
Output power (MW)	28	40	52

[a] The following parameters are used: Electron beam peak current = 200 (A), Rectangular waveguide size = $2b \times b$, Input millimeter wave power = 1 kW.

However, we can work on the weak superradiance regime because larger waveguide dimensions are necessary to reduce the waveguide parameters.

6. Summary

Some important experimental issues, such as the coupling and the detection of the radiation and 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 under way. 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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