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Section A

1-D simulation model of an FEL with a plasma background

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In order to supply shorter wavelengths wigglers in the FEL configuration, there is a significant ongoing research effort. Among approaches to decreasing λ_w is the replacement of the magnetic undulator with an electrostatic plasma wave undulator [1]. This configuration is based on using a short wavelength, large amplitude relativistic plasma wave as undulator through which a moderately relativistic electron beam is injected.

The study of the interaction of a relativistic electron beam (REB) with a background plasma (or a gas) has been of interest in many areas of plasma and beam physics over the years. Relativistic electron beams have been injected into gas and plasma to develop high-power microwave and X-ray sources, and to study plasma accelerator concepts. The types of interaction depend on the experimental parameters such as the electron beam density, plasma density, and the geometry of the experiments. There can be several types of beam–plasma interactions. For example, electromagnetic waves can be produced by the scattering of electrostatic plasma waves off self-consistently produced ion-acoustic waves [2]. In this case, the plasma medium has a moderate density ($n_p \approx 10^{120c2}$ cm^{-3}) and the electron beam density has the ratio of $10^{-4} < n_b/n_p < 10^{-2}$ [2].

The plasma medium can function as the undulator itself [3], or the medium can be used to fill the FEL cavity in the wiggler magnets [4]. For the former case, the electrons propagate either parallel to or perpendicular to the wave fronts of the plasma waves, and emits radiation oscillating in the alternating wave's electrostatic field [1]. For the plasma wave undulator, electron trajectories are bent by the electric field of the travelling plasma wave which can be produced by laser beatwave excitation, laser wakefield excitation, or plasma wakefield excitation. In this scheme the medium plasma should be dense ($n_p \approx 10^{17}$ cm^{-3}), and the electron beam should have a high density ($n_b \approx 10^{15}$ cm^{-3}) [3].

Other plasma based undulators have been investigated in recent years. The operation of plasma FELs are based on small transverse oscillations of relativistic electron beams in excited fields. In the ion ripple laser electrons oscillate in the transverse electric field of the ripple which is created by the excitation of an ion acoustic wave in a neutral plasma [5].

There can also be the mechanism of ion focusing, and this has been successfully employed in accelerator work. In the ion channel laser electron oscillations are due to electrostatic focusing in the channel [6,7,8].

In this synopsis we consider the so-called ion channel laser using the Maxwell Lorentz formulation. Then we investigate system characteristics using a many particle simulation.

The motion of an electron in the ion focused region with scattered EM fields is given as

$$\frac{d\gamma}{dz} = -\frac{k a_s a_p}{\gamma} \sin \psi, \tag{1}$$

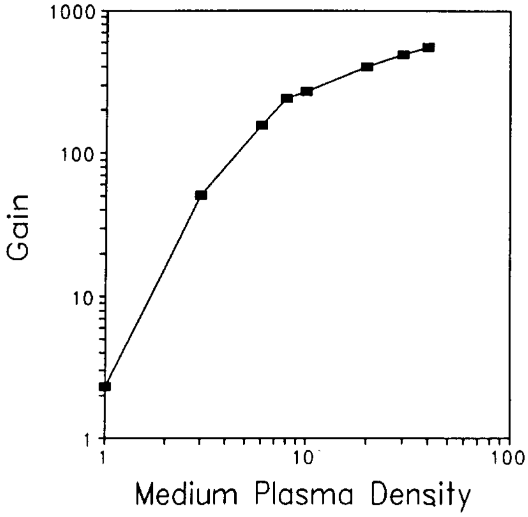

Fig. 1. Gain versus the medium plasma density (in units of 10^{10} cm^{-3}).

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$$\frac{\mathrm{d}\psi}{\mathrm{d}z} = k_s \beta_z - k_s + k_\beta \left(1 - \frac{a_s}{2a_p}\cos\psi\right) + \frac{1}{2}\frac{k_s a_s a_p}{\gamma^2}\cos\psi + \frac{\mathrm{d}\phi}{\mathrm{d}z}, \tag{2}$$

where

$$\psi = (\omega_s - \omega_\beta)t - k_s z + \phi.$$

Note that ω_β is the oscillation (betatron) frequency of the electron in the ion space charge field. Here γ is the relativistic factor of the electron beam, k_β and k_s are the wavenumbers of the pump field (that is, transverse betatron motion due to the ion space charge field) and scattered radiation, ϕ is the phase of the scattered e.m. radiation, and a_s and a_p are the normalized amplitude of the scattered e.m. wave and pump wave, respectively. a_p is related to other variables as $a_p = ak_s/2\gamma$, where a is the electron beam radius.

Assuming a single frequency, the radiation field and pump field evolve according to

$$\frac{\mathrm{d}a_s}{\mathrm{d}z} = \kappa\left\langle\frac{a_p \sin\psi}{\gamma}\right\rangle, \tag{3}$$

$$\frac{\mathrm{d}a_p}{\mathrm{d}z} = -\tfrac{1}{2}a_s k_\beta \sin\psi, \tag{4}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}z} = \kappa\left\langle\frac{a_p}{a_s}\frac{\cos\psi}{\gamma}\right\rangle - \kappa\left\langle\frac{1}{\gamma}\right\rangle, \tag{5}$$

where $\kappa = \omega_p^2 F/2k_s c^2$ (F is the beam filling factor, and $\langle \cdots \rangle$ is the ensemble average. Similar formulations can be found in Refs. [7,8].

Using Eqs. (1)–(5), we calculate numerically the amplified wave amplitude throughout the interaction region and the nonlinear efficiency (or power gain) of the FEL system following the self-consistent evolution of the amplitude and phase of the wave. Radiation propagation is described by a paraxial difference method on a spatial grid on axis with 600 grid points. About 400 test particles loaded with uniformly distributed phases move in γ, ψ space according to Eqs. (1) and (2).

Fig. 1 shows the power gain as a function of the medium plasma density. The electron beam current density is 10^7 (A/m^2), the beam energy $\gamma = 4$, and the initial pump strength is 0.8. The results show the exponential gain growth. Next, we investigate the effects of energy spread. For a low oscillation frequency case (i.e. moderate medium plasma density), the system does not exhibit severe gain decrease with increasing energy spread, but for a relatively high oscillation frequency case, the results show a drastic degradation in gain. In addition, we note that there exists no significant gain for the UV and X-ray regions in contrast to previous studies [7,8], and for higher electron beam energy the gain decreases rapidly.

In an FEL with a plasma background, the electron beam passing through the undulator plasma might begin to thermalize due to various particle–particle and wave–particle interactions. Thus the effective interaction region becomes contracted, preventing coherence of the e.m. wave. To avoid such beam–plasma interaction the electron beam should be bunched and narrower than the skip depth.

In this study, we perform a particle simulation of beam transport along the interaction region for various pump conditions using the one-dimensional Maxwell–Lorentz formulation. The model operating parameters are chosen from on-going (or planned) experiments.

The main results can be summarized as follows:

(1) The ion channel laser may be a promising candidate for producing coherent e.m. radiation in the microwave and submillimeter region.

(2) The electron beam quality is crucial, especially for the high frequency region (high medium plasma density region).

(3) The overall performance depends on the undulator parameter a_p (pump strength) which is a function of beam radius, beam energy, and betatron frequency. Another important parameter is the medium plasma density.

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