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REPORT OF THE WORKING GROUP ON FAR-FIELD ACCELERATORS*

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ABSTRACT

MASTER

This report describes the work of the Group on Far Field Accelerators. The work was focused on two accelerator schemes, the Inverse Free Electron Laser and the Two Wave Device. The possibilities and limitations of these two accelerators are discussed, as well as some of the requirements on the laser necessary to reach very high energies. A conceptual design of a single pass Inverse Free Electron Laser is presented.

I. INTRODUCTION

The very high electric field obtainable in a laser beam makes the idea of a laser accelerator attractive. This laser accelerator is even more attractive if the acceleration process does not require the presence of a plasma or other media or of a metallic structure at a wavelength distance from the beam, thus avoiding problems of electrical breakdown and beam intensity limitations typical of media or near field accelerators.

A far field accelerator, utilizing a laser beam in vacuum and with any material structure being at a distance from the laser and particle beam large compared to the radiation wavelength, offer some important advantages with respect to other laser accelerator concepts:

- 1) The acceleration region is far removed from all material boundaries, thus avoiding problems of material breakdown and plasma formation.
- 2) The accelerated beam is not constrained to move near a material boundary, thus avoiding problems of emittance limitations, and of intensity limitations due to the electromagnetic interaction of the beam with the material boundary.

The acceleration of particles utilizing a radiation field, laser field, and some combination of static magnetic fields has been proposed by many authors.¹⁻⁴ The work of the group on far field accelerators has been dedicated to the study of the Inverse

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Free Electron^{5,6} (IFEL) and of the Two Wave Device⁷ (TWD). It is worth noting that an experimental proof of the IFEL has been obtained recently at Los Alamos, Mathematical Sciences Northwest and TRW.⁸ For these two systems the group has worked out a set of scaling laws to establish the maximum accelerating gradient obtainable. A conceptual design of an inverse free electron laser has also been done and has been very useful in understanding the limits on the maximum beam energy and other accelerator parameters.

There are two types of limits on the maximum beam energy, one related to the laser accelerating field and one to synchrotron radiation losses of the electron beam. To obtain high electron energies one needs a number of accelerating regions where the laser beam is focused to a small size. One acceleration region is shown in Fig. 1 for an IFEL; a laser beam is brought to a focus in an undulator where the acceleration takes place. For a TWD the undulator is to be replaced by a microwave structure.

A system with many acceleration regions can be obtained either by multiple focusing of one laser beam, as in Fig. 2, or by using a number of laser beams, each focused only once, as in Fig. 3. In the first case one needs to solve the problem of transmitting and focusing a high power laser beam, with a power of the order of 10^{13} - 10^{14} W, over distances of the order of 10^3 m, periodically focusing the beam to a spot size of the order of 10^{-3} m. In the second case the main problem is to keep the phase coherence of the amplified laser beams so that the particles remain in step with the accelerating field.

The multiple focusing or multiple beam design are common also to other laser accelerator schemes and deserve a careful study. In this report we have chosen to simplify the accelerator design by considering only one acceleration region. This, of course, limits the maximum beam energy.

Synchrotron radiation losses are unavoidable in an inverse free electron laser accelerator, and are produced when the beam moves sideways in the undulator. These losses can be minimized by a proper choice of undulator parameter, but they remain the ultimate limitation to the maximum beam energy.

In what follows we will first discuss the basic physics of the Inverse Free Electron Laser and of the Two Wave Device. We will then obtain some scaling laws and discuss a conceptual design of a far field accelerator.

II. FAR FIELD ACCELERATORS

Consider one relativistic electron moving along the z-axis and subject, over a certain distance, to a transverse force F_x producing a transverse oscillation (Fig. 4). Assume

$$F_x = A e^{i(\omega t - K_z z)} \quad (1)$$

and

$$z = \beta_z ct \quad (2)$$

The transverse velocity is

$$\beta_x = -i \frac{A}{m\gamma c} \frac{1}{\omega_p - K_p \beta_z c} e^{i(\omega_p t - K_p z)} \quad (3)$$

where m is the electron mass, γ its energy in rest energy unit. Note that the energy change is proportional to $\beta_x F$ and has zero average value.

Add to the system a laser beam, propagating along z , which we represent as a plane electromagnetic wave

$$E_x = E_0 e^{-i\omega_L(t-z/c) + i\phi_0} \quad (4)$$

We have now an energy exchange between the electron and the wave. The change in electron energy is

$$\frac{d\gamma}{dt} = \frac{eE_x \beta_x c}{m c^2} = -i \frac{eE_0 A e^{i[\omega_p - K_p \beta_z c - \omega_L + \omega_L \beta_z]t + i\phi_0}}{m^2 c^2 \gamma (\omega_p - K_p \beta_z c)} \quad (5)$$

The average value of $d\gamma/dt$ is non-zero if

$$\omega_L(1-\beta_z) = \omega_p - K_p \beta_z c \quad (6)$$

and this condition can also be obtained from energy and momentum conservation. If (6) is satisfied we can rewrite (5) as

$$\frac{d\gamma}{dt} = \frac{e E_0 A}{m^2 c^2 \gamma (\omega_p - K_p \beta_z c)} \sin \phi_0 \quad (7)$$

describing acceleration if $\sin \phi_0 > 0$ or deceleration if $\sin \phi_0 < 0$.

We will not discuss here the effect of oscillation around the phase ϕ_0 , and the acceptance in energy of the accelerator. This discussion can be found in reference 4 for the IFEL case. We limit the discussion to the evaluation of the acceleration rate described by (7) for a given ϕ_0 .

To describe the electron oscillations and the energy change it is convenient to introduce the following quantities: electron oscillation wavelength

$$\lambda_0 = \frac{2\pi c}{\omega_p - K_p \beta_z c} \quad (8)$$

the force parameter

$$K = \frac{A \lambda_o}{2\pi m c^2} \quad (9)$$

Using (8), (9), we can write the amplitude of electron transverse velocity, β_x , as

$$\beta_x = \frac{K}{\gamma} \quad (10)$$

and the electron oscillation amplitude as

$$a = \frac{\lambda_o K}{2\pi\gamma} \quad (11)$$

With the help of (8), (9) and (10) we can rewrite the maximum accelerating gradient (7) as

$$mc^2 \frac{d\gamma}{dz} = \frac{e E_o K}{2\gamma} \sin \phi_o \quad (12)$$

III. THE IFEL AND TWD

In Section 2 the transverse force acting on the beam has not been specified. We consider now two particular ways to produce this force: one with a magnetic undulator, the other with a slow TE electromagnetic wave propagating nearly parallel to the electron beam. The first case corresponds to an IFEL, the second to a TWD.

In the IFEL case⁴ the force produced by an undulator with a magnetic field B_w , is obtained by taking in (1).

$$A = e B_w \beta_z \quad (13)$$

$$\omega_p = 0, \quad K_p = \frac{2\pi}{\beta_z \gamma_o} \quad (14)$$

We then have from (9)

$$K = \frac{e B_w \lambda_o}{2\pi m c^2} \quad (15)$$

The synchronism condition (6) becomes

$$\omega_L = \frac{2\pi c}{\lambda_o (1 - \beta_z)} \quad (16)$$

Since $\beta_z = (1 - \beta_x^2)^{1/2} \approx 1 - (1 + K^2)/2\gamma^2$, (16) can also be written in the more familiar form

$$\lambda_L = \frac{\lambda_o (1+K)}{2\gamma^2} \quad (17)$$

For a slow TE wave propagating at an angle θ to the z axis, with velocity c/n and an electric field amplitude E_p , we have⁶

$$A = e E_p (\cos \theta - \beta_z n) \quad (18)$$

$$K_p = \frac{n \omega_p \cos \theta}{c} \quad (19)$$

$$\omega_L = \omega_p \frac{1 - n \beta_z \cos \theta}{1 - \beta_z} \quad (20)$$

$$\lambda_o = \frac{2\pi n \cos \theta}{K_p (1 - n \beta_z \cos \theta)} \quad (21)$$

$$K = \frac{e E_p \lambda_o (\cos \theta - \beta_z n)}{2\pi m c^2} \quad (22)$$

IV. SCALING LAWS

In the TWD case if one chooses

$$1 - n \beta_z \cos \theta \approx 0 \quad (23)$$

i.e. wave velocity nearly equal to particle velocity, the quantities λ_o , K , β_x become large and $d\gamma/dz$ increases. Pantell and Smith⁶ have shown that one can get a solution of the electron equations of motion in the combined slow wave and laser field, such that

$$1 - n \beta_z \cos \theta \propto \gamma^{-2/3} \quad (24)$$

From (24) and (18) to (22) one can obtain the scaling of the electron oscillation and of the acceleration rate with energy

$$\lambda_o \propto \gamma^{2/3} \quad (25)$$

$$K \propto \gamma^{2/3} \quad (26)$$

$$\beta_x \propto \gamma^{-1/3} \quad (27)$$

$$a \propto \gamma^{1/3} \quad (28)$$

$$\frac{d\gamma}{dz} \propto \gamma^{-1/3} \quad (29)$$

More exactly for the acceleration rate one has⁶

$$mc^2 \frac{d\gamma}{dz} = 2 \times 10^{-2} \left(\frac{\lambda_L E_p}{\gamma} \right)^{1/3} \left(\frac{n^2 - 1}{n} \right)^{1/3} e E_0 \frac{eV}{m} \quad (30)$$

with E_p and E_0 in V/cm and λ_L in μm .

When γ changes n and or θ have to be adjusted to satisfy the synchronism condition (20).

The scaling of the acceleration rate, (29), has a weak dependence on γ . However, as γ increases the oscillation amplitude increases, as shown by (28), and this may require a larger dimension of the laser beam which would reduce E_0 .

In the IFEL case the acceleration rate is given by equation (12), with K defined in (15) and the synchronism condition by (16) or (17). Since both K and/or λ_0 have to be a function of γ to satisfy (17), the dependence of the acceleration rate on γ is more complicated than γ^{-1} . As an example, let us assume that the undulator magnetic field is kept constant and that one changes λ_0 to satisfy (17) for a given λ_L . For $K > 1$ one obtains the scaling

$$\lambda_0 \propto \gamma^{2/3} \quad (31)$$

and all other quantities scale as in (26) to (29).

Assuming again for simplicity $K > 1$, one obtains for $d\gamma/dz$ the expression

$$mc^2 \frac{d\gamma}{dz} = \frac{e E_0}{\gamma^{1/3}} \left(\frac{e B_w \gamma_L}{\pi mc^2} \right)^{1/3} \sin \theta_0, \quad B_w = \text{constant} \quad (32)$$

As an example, if we assume for the TWD $\lambda_L = 10 \mu m$, $E_p = 10^6$ V/m, $E_0 = 10^{11}$ V/m, $n = 1.5$, $\gamma = 10^3$ we obtain from (30) an accelerating field

$$mc^2 \frac{d\gamma}{dz} = 400 \text{ MeV/m}$$

In the IFEL case if we use the same laser wavelength and electric field and we assume $B_w = 0.12$ T and $\lambda_0 = 50$ cm we obtain at $\gamma = 10^3$

$$mc^2 \frac{d\gamma}{dz} = 600 \text{ MeV/m}$$

V. LASER FOCUSING AND RADIATION LOSSES

A simple far field accelerator can be designed considering a single acceleration region of length L and assuming a gaussian laser beam focalized to a waist w_0 related to the radiation wavelength and the length L by⁹

$$2\pi w_0^2 = L\gamma \quad (33)$$

The change in beam area is then given by

$$w^2 = w_0^2 \left(1 + \frac{4z^2}{L^2}\right) \quad (34)$$

For a laser beam of total power W the electric field is given by

$$E_0 = \left(\frac{2WZ_0}{\pi w^2}\right)^{1/2} \quad (35)$$

when $Z_0 = 377 \Omega$.

Since in the acceleration region, $|z| < L/2$, the waist variation is small, we simplify the calculation by assuming $w = w_0$ and

$$E_0 = \left(\frac{4W Z_0}{\lambda_L L}\right)^{1/2} \quad (36)$$

Using (30), (36), we obtain for a single pass TWD of length L and assuming that the final energy, γ_f , is much larger than the initial energy, γ_0 ,

$$\gamma_f \approx 10^{-4} (WL)^{3/8} E_p^{1/4} \lambda_L^{-1/8} \quad (37)$$

Note the weak dependence on the laser wavelength, λ_L . For a laser power $W = 10^{14}$ W, $\lambda_L = 10 \mu\text{m}$ and $E_p = 10^6$ v/m we obtain from (37)

$$\gamma_f = 2.4 \text{ GeV} \quad \text{for} \quad L = 4 \text{ m}$$

$$\gamma_f = 30 \text{ GeV} \quad \text{for} \quad L = 4 \times 10^3 \text{ m}$$

showing that the system is very effective for short acceleration length (an average accelerating field of 600 MeV/m for $L = 4$ m) but not for large L . This is a consequence of (33) which implies a large w_0 , and hence a small electric field, as given by (36), for large L . To accelerate to high energies it is necessary to use multiple acceleration region as in Fig. 2 or 3. Synchrotron radiation losses are small for a TWD.⁷ For the same value of λ_L ,

W and E_p used before and for $\gamma = 10^6$ these losses are smaller than 1 MeV/m.

Synchrotron radiation losses can be an important factor in an IFEL. In this case the energy lost per unit undulator length is

$$S = \frac{8}{3} \pi^2 \frac{r_e}{\lambda_o^2} K^2 \gamma^2 mc^2 \quad (38)$$

The condition

$$mc^2 \frac{d\gamma}{dz} > S \quad (39)$$

can be written as

$$e E_o > \frac{8}{3} \pi^2 \frac{r_e}{\lambda_o^2} K \gamma^3 mc^2 \quad (40)$$

In the case discussed previously in which one keeps $B_w = \text{constant}$ in the undulator and $\lambda_o \propto \gamma^{2/3}$ we obtain

$$e E_o \propto \gamma^{7/3} \quad (41)$$

A scaling with $\lambda_o = \text{constant}$ and $B_w \propto \gamma$ gives a less favorable result, $e E_o \propto \gamma^4$, equal to that of a circular accelerator. In the case $B_w = 0.1 \text{ T} = \text{constant}$ we obtain a synchrotron radiation loss, at $\gamma = 10^5$, $S = 4 \times 10^4 \text{ eV/m}$. At the same energy the undulator period is 12 m, and the electron oscillation amplitude is 2.4 mm.

VI. AN IFEL ACCELERATOR

In this section we want to summarize some of the previous results for an IFEL and make a conceptual design of a single pass IFEL accelerator. We first rewrite the formulae we want to use:

a) synchronism condition, eq. (17)

$$\lambda_L = \frac{\lambda_o (1+K^2)}{2\gamma^2} \quad (42)$$

b) acceleration rate, eq. (12)

$$mc^2 \frac{d\gamma}{dz} = \frac{e E_o K}{\gamma} \sin \phi_o \quad (43)$$

c) synchrotron radiation losses; using (38) and (39) we write this as

$$\frac{d\gamma}{dz} > \frac{8}{3} \pi^2 \frac{r_e}{\lambda_o^2} K^2 \gamma^2 \quad (44)$$

d) transverse beam oscillation amplitude, eq. (11)

$$a = \frac{\lambda_o K}{2\pi\gamma} \quad (45)$$

e) accelerator length, eq. (33), and corresponding laser electric field for given laser power, W, eq. (36)

$$L = \frac{2\pi w_o^2}{\lambda_L} \quad (46)$$

$$E_o = \left(\frac{4WZ_o}{\lambda_L L} \right)^{1/2} \quad (47)$$

We integrate (43), (42) assuming, for simplicity, $K > 1$ and in the two cases $\lambda_o = \text{constant}$ or $B_w = \text{constant}$. This gives for the final electron energy, $mc^2 \gamma_f$, the value

$$mc^2(\gamma_f - \gamma_o) = e \left(\frac{8W Z_o L}{\lambda_o} \right)^{1/2} \sin \phi_o, \text{ if } \lambda_o = \text{constant} \quad (48)$$

or

$$\gamma_f^{4/3} = \gamma_o^{4/3} + \frac{4}{3} \frac{e}{mc^2} \left(\frac{4W Z_o L}{\lambda_L} \right)^{1/2} \left(\frac{e B_w \lambda_L c}{mc^2} \right)^{1/3} \sin \phi_o, \quad (49)$$

if $B_w = \text{constant}$

γ_o being the initial value. Since γ_f increases with z along the accelerator, λ_o and/or B_w have also to increase. Notice that there is no dependence on λ_L in (48) and a very weak dependence in (49).

The maximum beam current, I_B , is determined either by energy conservation

$$I_B < \frac{W}{mc^2 \gamma_f} \quad (50)$$

or by the condition that the defocusing electric field produced by the beam itself be less than the external focusing and

accelerating field.¹⁰ This last condition is in most cases weaker than (50).

The final longitudinal beam energy spread is determined by the depth of the trapping potential,⁴

$$\frac{\Delta\gamma}{\gamma} = \left(\frac{e E_o K \lambda_o}{\pi m c^2 \gamma^2} \right)^{1/2} \left(\cos\phi_o - \left(\frac{\pi}{2} - \phi_o \right) \sin\phi_o \right)^{1/2} \quad (51)$$

Using eqs. (42) to (51) we can make a conceptual design of a 4 GeV IFEL accelerator, obtaining the parameters of Table I. The laser parameters used in this table correspond to an existing Nd laser.

VII. CONCLUSIONS

The TWD and IFEL are similar in the basic physics principles. The substitution of the static undulator magnetic field of the IFEL with a slow microwave field in the TWD reduces synchrotron radiation losses at high electron energies.

Both the TWD and IFEL can produce GeV beams in a single pass with an accelerator length of the order of tens of meters. To produce higher energies it is essential to use a system with many acceleration regions and solve the related laser beam focusing problem.

Further studies are needed to design a multistage accelerators for very high energies, optimizing the variation of the refractive index for a TWD or of the undulator parameters for an IFEL, to minimize the total accelerator length and the synchrotron radiation losses.

It is worth noting that in an accelerator based on the IFEL or TWD concept, the electron beam is bunched on the scale of the laser wavelength and can produce intense spontaneous radiation at the harmonics of the laser frequency.

TABLE I

	$\lambda = 10 \text{ cm}$ (constant) o	B = 1 T (constant) w
<u>Laser Parameters</u>		
Power, W		$2 \cdot 10^{13} \text{ W}$
Pulse duration, τ		1 ns
Spot size, w_0		0.25 cm
Wavelength, λ_L		1 μm
Electric field, E_0		$2.8 \cdot 10^{10} \text{ V/m}$
Interaction length, L		39 m
<u>Ondulator Parameters</u>		
Period, λ_0	10 cm	$3.8 \rightarrow 23 \text{ cm}$
Magnetic field	$0.31 \rightarrow 3.8 \text{ T}$	1 T
Synchronous phase ϕ_0	$\pi/3$	$\pi/3$
<u>Electron Beam Parameters</u>		
Energy, $m_0 c^2 \gamma_f$	250 MeV $\rightarrow$ 4.2 GeV	250 MeV $\rightarrow$ 3.8 GeV
Current, I_B	<5 KA	<5 KA
Beam radius, r_B	0.2 cm	0.2 cm
Average accelerating field	101 MeV/m	90 MeV/m
Oscillation amplitude, a	0.007 cm	10^{-2} cm
Energy spread	10^{-4}	10^{-4}
Synchrotron radiation loss at γ_f	300 keV/m	20 keV/m

FIGURE CAPTIONS

- Fig. 1 Schematic representation of an acceleration region. A laser beam and an electron beam traverse an undulator magnetic field of length L . The laser beam profile is assumed gaussian with a waist radius w_0 .
- Fig. 2 Conceptual design of an accelerator with multiple acceleration regions and laser beam refocusing.
- Fig. 3 Conceptual design of an accelerator using multiple laser beams and acceleration regions.
- Fig. 4 Electron trajectory in undulator. The period and amplitude of oscillation are λ_0 and a .

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FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4