A High Energy e^+-e^- Collider using an Inverse Free Electron Laser Accelerator

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1. Introduction

Using existing acceleration techniques, the cost and complexity of high energy lepton-lepton and hadron-hadron colliders, increases rapidly with energy. This has lead to recognize the importance of searching for new acceleration mechanisms, which might reduce the cost per unit particle energy and allow us to continue to explore high energy physics in new energy regions.

Among the possible acceleration schemes the ones using the very large electric field obtainable in laser beams, have been receiving much attention. A review of much of the work done on laser accelerators can be found in the Proceedings of a Workshop on Laser Acceleration of Particles, held at Los Alamos in March, 1982.[1] In this Workshop laser accelerators were divided in three groups: media, near field and far field accelerators. In the last group one finds the "Inverse Free Electron Laser Accelerator: (IFELA).[2]

In this paper I want to discuss this laser accelerator scheme, and to show that it can be used to design a 300 GeV electron-positron collider with a luminosity of 10^{32} $cm^{-2}s^{-1}$, and an average accelerating field between 200 and 100 MeV/m.

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One important advantage of the IFELA is that the energy given to the electron is obtained from a far field, i.e. a field propagating in vacuum. Thus one can avoid all problems of electrical breakdown and beam intensity limitations[3] associated with near field accelerators, like linacs or grating accelerators.

2. Basic Physics of an IFELA

In the free electron laser (FEL) the energy exchange between a plane electromagnetic wave propagating in vacuum and an electron is obtained by giving to the electron a velocity component parallel to the wave electric field[2]. This transverse electron velocity is produced by an undulator magnet.

Let z be the wave direction of propagation, coinciding with the undulator axis, and x,y two orthogonal axes. We consider for simplicity the case of a helical undulator and a circularly polarized wave. The undulator field $\underline{B_o}$ is

$$B_{ox} = B_o \cos (2\pi z/\lambda_o) \tag{1}$$

$$B_{oy} = B_o \sin (2\pi z/\lambda_o) \tag{2}$$

where λ_o is the undulator period. The electric field of the laser beam is

$$E_{ox} = A_o \sin \left[(2\pi/\lambda)(z - ct) + \phi_o\right] \tag{3}$$

$$E_{oy} = A_o \cos \left[(2\pi/\lambda)(z - ct) + \phi_o\right] \tag{4}$$

For relativistic electrons, with an energy γ, measured in rest energy units $m_o c^2$, such that $\gamma >> 1$, the electron trajectory is determined, to order $1/\gamma^2$, by the undulator only.[6] Assuming for the electron velocity $\underline{\beta}$ (in units of the light velocity, c):

$$\beta_z = 1, \quad \beta_x, \beta_y << 1 \quad \text{and} \quad \gamma >> 1$$

the trajectory is a helix[4,5] of radius

$$a = \lambda_o K/2\pi\gamma \tag{5}$$

and velocity

$$\beta_x = \frac{K}{\gamma} \cos (2\pi z/\lambda_o) \tag{6}$$

$$\beta_y = \frac{K}{\gamma} \cos (2\pi z/\lambda_o) \tag{7}$$

where the "undulator parameter", K, is defined as

$$K = (e\, B_o \lambda_o)/(2\pi m_o c^2) \tag{8}$$

Using (3), (4), (5) and (6) the equation describing the electron energy change is[6]

$$\frac{d\gamma}{dt} = \frac{eA_o K}{m_o c\gamma} \sin\Phi \tag{9}$$

where Φ, the phase of the electron oscillation relative to the wave, is

$$\Phi = \frac{2\pi}{\lambda_o} z + \frac{2\pi}{\lambda} (z - ct) + \phi_o \tag{10}$$

For a net energy exchange the phase Φ in (9) must be constant or slowly changing. For an electron moving in the longitudinal direction with velocity β_z the change in the wave phase in one undulator period is

$$\Delta = \frac{2\pi}{\lambda} (1 - \frac{1}{\beta_z}) \lambda_o \tag{11}$$

If we require that Δ be equal to 2π, the change in electron oscillation phase in one period, we obtain the "synchronism condition"

$$\lambda = \lambda_o \frac{\beta_z - 1}{\beta_z} \tag{12}$$

or also, expressing β_z in terms of γ and β_x, β_y,[6]

$$\lambda = \frac{\lambda_o}{2\gamma^2} (1 + K^2) \tag{13}$$

If (13) is satisfied the phase Φ in (9) is a constant, Φ_o, and the energy will increase or decrease according to whether $\sin\Phi_o < 0$ or $\sin\Phi_o > 0$. For given λ, λ_o and K equation (13) defines a value γ_R of the energy which we call the resonant energy.

The synchronism condition (13) requires that as a particle, having $\gamma = \gamma_R$, is accelerated either λ_o or K have to change in order to continue to satisfy (13).[7] In most of what follows we will consider the acceleration of a particle satisfying (13) and

(9) with $\Phi = \Phi_o$ = constant. The effect of a deviation from the energy γ_R, as well as the effect of beam emittance and some undulator imperfections, is discussed in Section 7.

3. The Laser Beam

To evaluate the electric field acting on the electron and how the laser beam propagates we assume that this beam is in a gaussian mode[8] and that the acceleration takes place around a beam waist, formed in the transport system and characterized by a Rayleigh range R.

If z is the beam direction of propagation the laser beam r.m.s. transverse radius is given, as a function of z by[8]

$$r_L = r_o \left[1 + \left(\frac{z}{R}\right)^2\right]^{1/2} \tag{14}$$

with the minimum (waist) radius given by

$$r_o = (\lambda R/\pi)^{1/2} \tag{15}$$

For a given total power, W, in the laser beam the electric field at the waist and on axis is

$$A_o = (4WZ_o/\pi r_o^2)^{1/2} \tag{16}$$

with $Z_o = 377\Omega$.

Let us consider the case of a laser beam with wavelength λ = 1 μm, power W = 5 x 10^{13}W and R = 1 m. We then have $\pi r_o^2 = 10^{-6}$ m^2 and $A_o = 2.7 \cdot 10^{11}$ V/m. For this electric field V, and assuming $\gamma = 10^3$, $\sin \Phi_o = 1$, λ_o = 0.1 m, B_o = 0.45T. We obtain from (9) an acceleration rate

$$mc^2 \frac{d\gamma}{dz} = 1.1 \text{ GeV/m}$$

This order of magnitude estimate shows that the IFELA can provide an acceleration rate larger than what can be obtained from existing accelerators.

4. Scaling Laws

In addition to the acceleration rate we have to consider a number of other effects which are important in the accelerator design. One is the electron energy loss due to spontaneous synchrotron radiation emission, S, in the undulator magnet. The energy loss per unit length is[6]

$$S = \frac{8}{3} \pi^2 \frac{r_e mc^2}{\lambda_o^2} K^2 \gamma^2 \tag{17}$$

The radius of the helical trajectory, given by (5), must be smaller than the laser beam radius.

$$\alpha < r_L \tag{18}$$

This puts a limit to how much we can focus the laser beam.

An upper limit on the accelerated current, I_B, is given by energy conservation

$$I_B \, mC^2 \gamma < W \tag{19}$$

The formulae (17), (18), (19) together with (9) and (13) gives us a first order description of an IFELA. They can be used to obtain the scaling laws with energy of an IFELA. Let us assume that in (13) K is larger than one. Then for fixed laser wavelength the product $\lambda_o K^2$ must scale like γ^2 or, using (8), we must have

$$\lambda_o^3 \, B_o^2 \propto \gamma^2 \tag{20}$$

To illustrate the scaling with energy we consider only the two simple cases B_o = constant or λ_o = constant, although some intermediate case might be more convenient in an accelerator design. The scaling for the two cases considered is given in table 1. It is interesting to notice that in the case λ_o = constant the acceleration rate $\frac{d\gamma}{dz}$ does not decrease with energy but the synchrotron radiation loss increases with energy as in a circular accelerator, i.e. as γ^4. A reduction in radiation losses is obtained in the case B_o = constant, at the expense of a slight decrease of the accleration rate with energy. These considerations show that for a high energy accelerator we must use the case B_o = constant, to reach energies higher than those provided by storage rings.

5. Single pass intermediate energy IFELA

The simplest IFELA uses a single region where the laser beam is brought to a waist and where the acceleration takes place. To have a large average accelerating electric field one has to make the Rayleigh range and the undulator length, L, of the same order.

TABLE I: IFELA Scaling Laws

	B_o = constant	λ_o = constant
λ_o	$\gamma^{2/3}$	constant
B_o	constant	γ
K	$\gamma^{2/3}$	γ
$(\beta_x^2 + \beta_y^2)^{1/2}$	$\gamma^{-1/3}$	constant
a	$\gamma^{1/3}$	constant
$d\gamma/dz$	$\gamma^{-1/3}$	constant
S	γ^2	γ^4

We discuss now one example where we choose R=L. For a single pass system and assuming either λ_o = constant or B = constant we can calculate the final energy for given laser wavelength and power obtaining[6]

$$mc^2(\gamma_f - \gamma_o) = e\,(16WZL/\lambda)^{1/2}\sin\Phi \tag{21}$$

$$(mc^2\gamma_f)^{4/3} - (mc^2\gamma_o)^{4/3} = (4/3)e(8WZL/\lambda)^{1/2}\sin\Phi \tag{22}$$

An example of a single pass IFELA is given in Table 2. It is interesting to notice in (21), (22) the slow dependence of the final energy on the accelerator length, showing that this system can only be useful for energies of the order of 5 to 10 GeV.

6. Multistage IFELA

To accelerate electrons to energies of the order of a few hundred GeV, we must make the assumption that the laser beam can be focused periodically, so that its electric field remains large over a long distance.

TABLE 2: Single Pass IFELA

	λ_o=10cm (constant)	B_o=1 T (constant)
Laser Parameters		
Power, W	$2 \cdot 10^{13}$ W	
Pulse duration, τ	1 ns	
Spot size, r_o	0.25 cm	
Wavelength, λ	1 μm	
Electric field, A_o	$2.8 \cdot 10^{10}$ v/m	
Interaction Length, L	39 m	
Undulator Parameters		
Period, λ_o	10 cm	3.8 → 23 cm
Magnetic field	0.31 → 3.8 T	1 T
Synchronous phase ϕ_o	$\pi/3$	$\pi/3$
Electron Beam Parameters		
Energy, $m_o c^2 \gamma_f$	250 MeV → 4.2 GeV	250 MeV → 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

In this section we will assume that this is the case and study what accelerator performance one can obtain. A discussion of the laser focusing problem and one example of focusing system are discussed in a later section.

To calculate the final electron energy and the undulator characteristics we integrate equations (9), (13) for given laser wavelength, power and Rayleigh range. We assume the undulator magnetic field to remain constant to minimize synchrotron radiation losses.

The results of these calculations are given in Table 3. The first two cases use the same laser parameters, and differ only for the accelerator length. In the first case we can obtain nearly 180 GeV in 900 m with an average accelerating field of 200 MeV/m. In case two the length is increased to 3000 m but the energy only reaches 294 GeV, with an average accelerating field of 100 GeV/m. This reduction is due to the effect of synchrotron radiation losses which reduces the energy gain per meter at high energy.

The last two cases in Table 2 show the effect of a change in wavelength and that this effect has a small influence on accelerator parameters. The results shown in Table 3 are just examples of what an accelerator of this type can do and are not the result of an optimization study, which has still to be done.

In all cases considered we have also required the electron helix radius, (5), to be smaller than the laser r.m.s. radius at the waist, (15).

7. IFELA focusing and acceptance

The IFELA system provides both longitudinal and transverse focusing.[7] The transverse focusing is given in both the horizontal and vertical planes if one uses a helical undulator and in one plane only if one uses a transverse one. In this last case one needs to add quadrupoles to provide the missing focusing force.

The energy acceptance of the accelerator is given by:[7]

$$(\Delta E/E) = (2eA_o\lambda K)/(\pi mc^2(1 + K^2)) \qquad (23)$$

The oscillation wavelength produced by the focusing force in the helical undulator case is:[5]

$$\lambda_\beta = 2^{1/2}\lambda_o\gamma/K \qquad (24)$$

TABLE 3: Multistage IFELA

	1	2	3	4
Laser Wavelength, (μm)	1	1	3	10
Laser power, (TW)	50	50	50	50
Synchronous phase, $\sin\Phi_o$	.866	.866	.866	.866
Laser electric field, (TV/m)	0.22	0.22	0.22	0.11
Waist radius, (mm)	0.7	0.7	0.7	1.4
Electron energy, input, (MeV)	250	250	806	340
Undulator initial period, (cm)	3.8	3.8	10	10
Undulator field, (T)	1.0	1.0	1.3	1.0
Initial helix radius, (mm)	0.04	0.04	0.11	0.22
Accelerator length (m)	900	3000	2000	3000
Electron energy, final, (GeV)	175	294	292	307
Average Acceleration gradient (Mev/m)	193	98	98	102
Final helix radius, (mm)	0.4	0.5	0.8	2.2
Final undulator period(m)	3	4.3	5.1	9.4

The effect of the beam finite transverse dimension and of the angular spread can be reduced to that of an energy spread[9] and the resulting limitation on the emittance is:

$$\varepsilon < 2^{1/2}(\lambda\gamma/K)(\Delta E/E) \tag{25}$$

We have also considered the effect of an error in the length of the period of the undulator. This can be considered as equivalent to a change in longitudinal phase and hence an energy change. The results for the maximum possible period error, the maximum energy spread and emittance accepted are given in Table 4 for the case of the 300 GeV accelerator given before as case 2 in Table 3. One can see that the tolerance on the undulator period can be easily satisfied and that the acceptance compares well with that of existing accelerators, and allows for the acceleration of an intense beam, taking also into account the reduction of the beam emittance and energy spread with increasing beam energy due to the adiabatic damping.

TABLE 4: IFELA Acceptance and Error Tolerances

E(GeV)	K	λ_o(m)	$\frac{\Delta\lambda_o}{\lambda_o}$	$\Delta\lambda_o$(m)	$\frac{\Delta E}{E}$	ε(mrad)
0.25	3.5	$3.8\cdot10^{-2}$	$5\cdot10^{-2}$	$2\cdot10^{-3}$	$7.7\cdot10^{-2}$	$1.5\cdot10^{-5}$
294	400	4.3	$5\cdot10^{-4}$	$2\cdot10^{-3}$	$7\cdot10^{-4}$	$1.5\cdot10^{-6}$

8. An IFELA electron-positron collider

In this section we want to derive the parameters of an IFELA electron-positron collider capable of producing a luminosity, L, of the order of 10^{32} cm^{-2} s^{-1}m at an energy of 300 GeV. We will use the acceleration parameters given in Table 3 case 2.

For the luminosity and the diruption parameter, D, we use the formulae[10]

$$L = hfN/4\pi\sigma_\perp^2 \tag{26}$$

$$D = r_e\sigma\ \ N/\gamma\sigma_\perp^2 \tag{27}$$

where f is the system repetition rate, N is the number of particles per pulse, $\sigma_{/\!/}$ and $\sigma_{\perp}$ the longitudinal and transverse r.m.s. bunch dimension and h is an enhancement factor due to the pinch effect in the collision and depending on the value of D.[10]

For given laser power and laser pulse length we can only accelerate a certain number of particles to the final energy E_f; we assume

$$eNE_f = \eta 2\pi^{1/2}\sigma_{/\!/} W/c \tag{28}$$

where η is an efficiency factor and we have assumed a laser pulse length equal to $2^{1/2}\sigma_{/\!/}$. To calculate the electron bunch transverse dimension we assume for the injected beam a normalized emittance $\varepsilon_n = \pi\sigma_{\perp}^2\gamma/\beta$ of $2\pi\cdot 10^{-5}$ mrad and a beta function value at the crossing point of one centimeter. Then for E_f = 300 GeV we have

$$\sigma_{\perp} = .58\mu .$$

We can now use (27), (28), to calculate N and σ_{11} for given laser power, efficiency and disruption parameter. For $W = 5\cdot 10^{13}$W $\eta = .2$, D = 10 we have

$$\sigma_{/\!/} = 1.7 \text{ cm}, \quad N = 4.2\cdot 10^{10}$$

For D = 10 we can assume h = 1.5 and obtain from (26) a luminosity

$$L = 6.3f\cdot 10^{28} \text{ cm}^{-2}\text{s}^{-1}$$

or

$$L = 10^{32}\text{cm}^{-2}\text{ s}^{-1}, \text{ for } f = 1600$$

The average laser power needed is then

$$\langle W\rangle = 2\pi^{1/2} fW\sigma_{/\!/} /c = 16 \text{ MW}$$

and the laser energy per pulse is 10 KJ. With a plug to laser beam efficiency of 10% the total power needed for the collider operation is 320 MW.

One advantage of this system is that the energy to accelerate the particles can be put, by shaping the time duration of the laser pulse, only where the electron bunch is, while in a linac one has to fill the whole structure.

9. Laser Beam focusing with Metallic Wave Guide

The focusing of the laser beam over distances of the order of one kilometer, at power levels of 10^{13} - 10^{14} Watt and maintaining phase coherence is certainly the major problem of the IFELA and also of most of the other laser accelerator schemes. Much theoretical and experimental work will be needed to establish if and how this focusing is feasible, and any program of laser accelerator development will have to include this work. A discussion of some focusing system can be found in ref. 11.

In this section we want to give a very simple discussion of one possible focusing system based on a metallic wave guide. We assume this guide to be formed by two planes parallel to the z-y plane and separated by a distance "a".

We also assume that we are using a transverse undulator so that the electron trajectory is planar and in the z-y plane (the magnetic field of the undulator is in the x-direction).

The wave guide can be formed with two metallic strips having a width "w" larger than the separation "a" between them and a length in the z-direction equal to the accelerator length. The guide can transmit both $TE_{m,o}$ and $TM_{m,o}$ modes. The attuanation of the TM modes is much larger than for the TE modes and we will consider only the transmission of the laser beam in the TE configuration.

The $TE_{m,o}$ mode electric field can be written as:[12]

$$\underline{E} = A_o \hat{y} \sin ((\pi m/2)(1 - 2x/a)) \cdot \exp(-i\beta_m z) \qquad (29)$$

$$\beta_m = [(2\pi/\lambda)^2 - (m\pi/a)^2]^{1/2} \qquad (30)$$

The mode m can be thought of as the superposition of two plane waves propagating at an angle θ respect to the z axis with

$$\theta_m = m\lambda/2a \qquad (31)$$

The absorption loss in one reflection on the metallic plan depends on the angle θ_m and on the metal refraction index, n,

$$A = 4\theta_m \mathrm{Re}(1/n) \qquad (32)$$

Since the number of reflections per unit length is θ/a the loss per unit length can be written[12]

$$\alpha = (m^2\lambda^2/a^3)\ \mathrm{Re}(1/n) \tag{33}$$

The ratio of the field on the wall to the field on axis is:

$$E_{wall}/E_{axis} = (m\lambda/a)\ \mathrm{Re}(1/n) \tag{34}$$

To estimate how much of an input beam one can couple into the guide we can assume the input beam to be gaussian $E \propto \exp(-x^2/r_o^2)$, with r_o given by (15), and to expand it in plane waves. The fraction of the input power and of the input field coupled into the m-th guide mode is:[12]

$$f_m(\eta) = \left(\frac{2}{\pi}\right)^{5/2} \frac{1}{\eta} \left[\int_{-\pi/2}^{\pi/\ell} \cos(mu)\exp(-4u^2/\pi^2\eta^2)du\right]^2 \tag{35}$$

with

$$\eta = 2r_o/a \tag{36}$$

and

$$A_m = (\pi/2)^{1/4}\ \eta^{1/2}\ f_m(\eta) \tag{37}$$

The power fraction f_m has a maximum for the mode $m = 1$ when $2r_o/a = .707$. The value of this maximum is $f_1 = 98.9\%$. For the same value of $2r_o/a$ one also has $A_m \simeq 1$.

As an example let us consider the case $a = 4$ mm, $2\ r_o/a = .707$, $m = 1$, $\lambda = 1 \cdot 10^{-6}$m, $P = 5 \cdot 10^{13}$W; we then have

$$\theta_1 = 1.25 \cdot 10^{-4}$$

$$\alpha = 3 \cdot 10^{-7}$$

$$E_{wall}/E_{axis} = 5 \cdot 10^{-6}$$

$$E_{wall} = 10^6\ \mathrm{V/m}$$

We see from these numbers that the attenuation is rather small and the field on the wall is below the known damage threshold.[11]

As one can see from (33) the attenuation increases rapidly with the mode number. To obtain the small attenuation value given before it is very important to avoid any mode coupling as it might, for instance, be produced by surface irregularities. This means that the planes should be worked to optical quality.

Although the coupling efficiency to the guide can be very high the coupling region remains a critical area of this system and one should consider how to optimize it by using properly shaped surfaces.[11]

10. Conclusions

On the basis of the preceding discussion, the IFELA seems to offer the possibility of accelerating electrons up to energies of several hundred GeV. The beam intensity and beam emittance satisfy the requirements for high energy physics use and allow to obtain a good luminosity with an overall power consumption comparable with that of more conventional schemes. The high acceleration rate should keep the overall accelerator length and cost down.

The undulator can be built with permanent magnets; the required aperture is of the order of one centimeter so that its transverse dimensions are small. The undulator - wave guide system can then be very compact, it does not require any power supply and its cost might be low when compared with that of other accelerator structures.

If one can solve the problem of the laser beam transport and focusing system the remaining problem is the laser itself. Lasers producing peak power of the order of 10^{13} - 10^{14} Watt are currently being used in the laser fusion program. However they do not have neither the repetition rate nor the beam quality necessary for the IFELA. A high repetion rate is required also for a laser fusion reactor and the scientists working in this field are confident that it can be achieved.

Another very important requirement for an IFELA laser is a good efficiency. Again this is a problem in common with the laser fusion program. There are a number of lasers which can have an efficiency of the order of several percent. In particular the free electron laser might be able to reach an efficiency as high as 20% in the wavelength region of our interest, with a good optical beam quality.

Using a free electron laser as a driver the accelerator system would start with a low energy, high intensity electron beam which would be used to power the laser beam; this in turn would accelerate an electron beam injected in the IFELA from an electron storage ring, similarly to what is done in the Single Linear Collider at SLAC.

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DISCUSSION

Willis. What is the group velocity of the wave?

Pellegrini. Near to one. The electrons are relativistic. One can calculate the displacement between the laser pulse and electron bunch, but this is small. It does not cause a problem.

Lawson. I am not quite clear about your laser beam matching system. You match vertically, but what about the spread horizontally?

Pellegrini. In that plane one can choose a very long Rayleigh length, so that one doesn't need to focus as often. This has not been studied in detail and work remains to be done.

Johnsen. How severe are the tolerances? Also, now that you again have a waveguide has not the advantage of far fields disappeared?

Pellegrini. In answer to the second question, the advantage has only partly disappeared since the beam is still a large distance from the wall. For a near field accelerator it would be within 1 micron. Another advantage is that the waveguide has smooth walls and is not loaded with discs (which would give strong interaction with the wall).

The tolerance on the period of the undulator is 2 mm in a wavelength going from 4 cm to 4 metres; the tolerance on the magnetic field is a similar percentage.

Hand. Have you considered possible loss of synchronism due to quantum fluctuations at the high energy end of the accelerator? It may be more severe here than in a sychrotron, since the energy is higher and the buckets are smaller.

Pellegrini. The energy acceptance of the system should be good enough, but we haven't looked at this.

Billinge. You mentioned that the energy acceptance decreases as $1/\gamma$ Does not this imply that there is no energy damping and hence loss of particles in longitudinal phase space?

Pellegrini. No. The energy spread should decrease with energy as in any other system, so it would match the decreasing acceptance. There is adiabatic damping.

Hofmann. The spread in angle of the electron beam has to be smaller than k/γ.

Pellegrini. This is included as part of the emittance requirement.

Hofmann. Concerning the inverse Cherenkov accelerator, would not an intense beam ionize the gas and lose the refractive index?

Pellegrini. That might be a limit on intensity.

Richter. I wish you have invented this machine five years ago, because this device seems to be limited to a few hundred GeV in energy. So it would have been a great replacement for something like LEP.

This type of machine also has a severe power problem. 10^{32} is the canonical luminosity for lower energy machines, not for those with 300 GeV on 300 GeV, where lower cross sections mean that one or two orders of magnitude more are needed. If that is so your 300 MW power source goes to 3-30 GW. It does not seem a good system for very high luminosities or very high energies.

Pellegrini. These certainly is an upper limit. When we met at Los Alamos nobody thought that there was any hope for such high energies. The limitation was thought to be a few GeV. We have tried to show that the proven FEL mechanism can go to 300 GeV. Maybe we can find some way to go even higher.

Palmer. In reply to Richter I should like to say that this was published in 1972, ten years ago not five. (J.A.P. 43, 3014). Of course the luminosity is a problem, but this is true also of conventional linacs with klystrons.

Pellegrini. But it is true that you lose efficiency in a laser, which is not as efficient as a klystron. On the other hand you only put the power where you need it, (where the electrons are), so the overall efficiency may be comparable.

Nation. Are there any possibilities of coherent effects (such as coherent synchrotron radiation)?

Pellegrini. This will be largely suppressed by the rather small waveguide, (4 mm), in which the beam travels, and will not be an important effect.

Motz. What do you propose for a first application of such a system? There has been no experiment on acceleration; an experiment on a device which would be useful is very desirable. Do you have any recommendation?

Pellegrini. There have been FEL experiments which can accelerate or decelerate electrons to a small extent. It would be desirable to do further experiments to accelerate by a reasonable amount.

Participant. I am still not convinced by your focusing system. You will have some thousands of modes in your 4 mm waveguide which are dispersive. You will not have coherence over long distances.

Pellegrini. The principal mode, which has low attenuation, will predominate.

(Further confused discussion, with question unresolved).

Pellegrini. For any system of this kind one needs very high powers, a high repetition rate and good optical beam quality, and no laser like this is cheap. There are CO_2 lasers which can produce this kind of power with good efficiency.

Voss. What does a free electron laser look like?

Pellegrini. If you want to design one like this, the problem is producing an electron beam which can provide this kind of power, with good repetition rate. Many schemes require such beams.

Sessler. This talk emphasized the importance of FEL as an accelerator or a power source for other accelerators. 'Two beam accelerators' are very interesting; a low energy beam generates radiation, which is then used to produce a high energy beam. We are doing an experiment to use an FEL to produce high power radiation in the millimetre range. This uses the ETA at Livermore which produces a 10 kA 5 MeV beam, and we hope by using about 1 kA of the beam to generate hundreds of MW peak power in the millimetre range. We have further plans to go to 10 microns using the 50 MeV ATA.

Motz. The key to these accelerators is the induction linac.

Sessler. You can have, say, a kilometre of induction linacs with wigglers; the induction linacs continuously provide the energy radiated in the wigglers.