PERSPECTIVES ON FREE-ELECTRON LASER DRIVEN VERY HIGH GRADIENT PARTICLE ACCELERATORS

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ABSTRACT

The prospects on the possible utilization of FEL sources for laser acceleration are reviewed.

1. INTRODUCTION

The possibility of realizing very high gradient accelerators is strongly dependent on the availability of reliable, efficient, high power and high repetition frequency electromagnetic radiation sources operating in the more convenient wavelength region (related to the chosen accelerating scheme). Under these aspects the free-electron laser (FEL)$^{1)}$ is one of the most promising sources. Indeed for the FEL the following general features can be outlined,

a) FEL performance mainly depends on low energy accelerator technology, which now presents a good level of reliability.

b) FEL overall efficiency can be, in principle, of the order of some percent.

c) Repetition frequency is not limited by heating of the active medium, as in gas or solid state lasers, and, with the present technology, can be of the order of many kHz.

d) The FEL radiation is now tunable from millimiter waves down to visible. In the near future VUV and, later, X-rays radiation would be obtained from this kind of source.

In order to have a better general insight into all these features and, in particular, into the power output which is possible from this source, we shall outline in section 2 the state of the art of FEL technology and, in section 3, the prospects for the near future. Finally, section 4 is devoted to some comments on the possible utilization of FEL sources for laser acceleration.

2. STATE OF THE ART OF FREE-ELECTRON LASERS

After the first succesful FEL experiment$^{2)}$ performed in 1977 at the Stanford University, a noticeable theoretical and experimental effort has been made in many laboratories. All the main theoretical problems are now well clarified as well as many experimental aspects (for example the undulator magnet technology) have reached a remarkable level of development. The scenario of the operating devices$^{3)}$ is reported in Table 1. The more special feature of the FEL source, i.e. the tunability, is displayed in Fig. 1, where the output peak power is reported versus wavelength. In Table 1 the intracavity peak power for the TRW oscillator is also reported. Indeed we can eventually utilize the intracavity beam itself, which can be extracted with a fast optical switching system. The value of the intracavity peak power (P_i) is just given by the ratio between the output one (P_o) and the total cavity losses Γ, i.e.

$$P_i = P_o/\Gamma. \tag{1}$$

TABLE 1

State of the Art for FEL Oscillators

Laboratory	Accelerator	$\mathcal{E}$ (MeV)	λ (μm)	P_i (W)	P_o (W)	E_i (MV/m)	E_o (MV/m)
Livermore	Induction Linac	4.5	8×10^3		8×10^7		
S. Barbara	Pelletron	3	400		5×10^{-3}		
Los Alamos	Linac	20	9-11		10^6		6
Stanford	Superconducting Linac	43	3.3		10^6		10
TRW	Superconducting Linac	66	1.6	1.7×10^8	5×10^5	200	10
ORSAY	Storage Ring	160	0.65		1		0.024

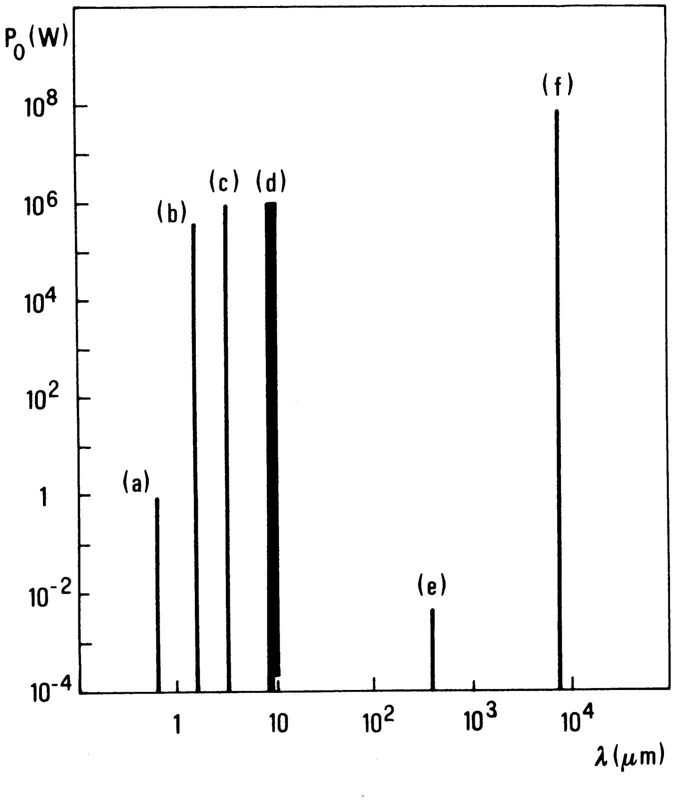

Fig. 1 Peak power vs wavelength for the operating FEL devices
(a) ORSAY
(b) TRW
(c) STANFORD
(d) LOS ALAMOS
(e) S. BARBARA
(f) LIVERMORE

In the first case we have a lower power laser beam, whose duration is of the same order as the electron beam, apart from the transient pulse rise time (typically many microseconds). In the second case the laser power is higher, but its maximum duration is roughly given by the round trip optical cavity transit time (some tens of nanoseconds).

Finally, in the last two columuns of Table 1, laser electric fields for Infrared FELs ($\lambda \lesssim 10$ µm) for a focalization corresponding to a Rayleigh length of four meters are reported for both output and intracavity laser beams.

Namely the electric field in the beam waist is given by,

$$E = \left(\frac{2PZ_o}{\pi w^2}\right)^{\frac{1}{2}} = \left(\frac{4PZ_o}{\lambda L}\right)^{\frac{1}{2}} \tag{2}$$

where we have defined

P = peak power

$w \doteq \sqrt{L\lambda/2\pi}$ = waist radius

λ = wavelength

L = Rayleigh length

Z_o = 377 Ω

3. PROSPECTS FOR FEL PERFORMANCE

It is not a simple task to foresee the best performances that will be possible to have in the future with a radiation source like the FEL one, whose development started only few years ago and where very few devices (only six!) up to now have been able to lase (see Table 1). However we can take advantage (for the near future) both from the well established electron accelerator technology and from the fact that the experimental FEL performances are in very good agreement with the previously derived theoretical predictions.

Let us start from some general considerations. Namely the output laser power P_o in a FEL is related to the electron beam current I and energy $\mathscr{E}$ by the relationship,

$$P_o[\mathrm{W}] = \eta \frac{\Gamma_T}{\Gamma} I[\mathrm{A}]\ \mathscr{E}[\mathrm{eV}], \tag{3}$$

where η is the efficiency in delivering energy from the electron beam to the laser one and

Γ_T = output cavity mirror transmissivity

Γ = total cavity losses

The intracavity power is given by (see eqs (1) and (3)),

$$P_i\ [\mathrm{W}] = \eta \frac{1}{\Gamma} I[\mathrm{A}]\ \mathscr{E}\ [\mathrm{eV}]. \tag{4}$$

As example, the main parameters for two FEL devices, operating at 10 and 100 μm wavelength respectively, are reported in Table 2. We focus our attention on these infrared devices mainly because for 10 μm the optical components technology is well developed (for CO_2 laser systems) while the wavelength of 100 μm (where high power standard sources are not available) appears very promising for some laser acceleration schemes (e.g. grating linac). In the examples of table 2 the efficiency is estimated of the order of 10%. This is a quite large value, if compared with that obtained up to now (~ 1%). However, theoretical considerations4) and recent experimental results5) show that this efficiency can be obtained in "tapered" or, in general, "multicomponent" FEL devices. The electron beam current (10 kA at 50 MeV) is that obtained in ATA6). We must stress, however, that the actual beam emittance of ATA is not enough good for an efficient FEL operation, so that further improvements of electron beam brightness are needed.

Table 2

Future Prospects for FEL Performance

I (A)	 (MeV)	λ (μm)	η (%)	Γ_T (%)	Γ (%)	P_i (GW)	P_o (GW)	E_i (GV/m)	E_o (GV/m)
10^4	50	10	10	1	2	2.5×10^4	25	10	1
10^4	50	100	10	1	2	2.5×10^4	25	3	0.3

4. FEL AS A LASER ACCELERATOR DRIVER

The convenience of utilizing a laser wave for particle acceleration is related to the possibility of realizing very high gradients, with respect to conventional linacs, by taking advantage of the very high electric field that is possible to obtain in the laser radiation. Under this aspect we can put, as a lower limit, a gradient of the order of 100 MV/m. The electric field of the laser wave must be of the same order of magnitude or more (apart high Q resonating structure accelerators, which are not easy to realize for short wavelengths, e.g. in the infrared). In particular the IFEL accelerating scheme7) requires an electric field which is many order of magnitude larger than the requested accelerating gradient. Indeed, in this case, the gradient G is just a small fraction of the laser electric field E_L

$$k = \frac{eB\lambda_u}{2\pi mc^2}$$

$$G \sim \frac{k}{\gamma} E_L, \qquad (5)$$

$$\gamma = \mathscr{E}/mc^2$$

where k/γ is the pinch angle of the electron in the IFEL, which is roughly given by

$$\frac{k}{\gamma} \sim \sqrt{\frac{2\lambda}{\lambda_u}}$$

λ = laser wavelength

λ_u = IFEL undulator period.

From eq. (1), (5) and (6), we obtain,

$$G = \left(\frac{8PZ_o}{\lambda_u L}\right)^{\frac{1}{2}} \quad . \tag{7}$$

From table 2 and eq. (7) we derive the IFEL gradient for both infrared sources

$$G \sim \begin{cases} 7\ \text{MV/m (intracavity beam)} \\ 0.7\ \text{MV/m (output beam)} \end{cases} \tag{8}$$

in the case

$$\lambda_u \sim 0.25\ \text{m}, \qquad L \sim 4\ \text{m} \quad . \tag{9}$$

From Tables, 1, 2 and eq. (8) we can outline the following conclusions,

a) the actual FEL sources (Table 1) can provide suitable electric field (> 100 MV/m) for laser acceleration only using intracavity beam,

b) future generation devices can, in principle, generate very large electric fields, both in intracavity and output beams, suitable for driving near field accelerators, where a large fraction of the laser electric field is utilized for acceleration;

c) for IFEL devices the situation is quite different from near field ones; indeed the gradients corresponding to the electric fields we hope to obtain from FEL sources in the future are very low (see eq. (8)). So that we can conclude that FEL devices are not suitable sources for IFEL accelerators.

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