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# A 4 to 0.1 nm FEL Based on the SLAC Linac*.

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Abstract

We show that using existing electron gun technology and a high energy linac like the one at SLAC, it is possible to build a Free Electron Laser operating around the 4 nm water window. A modest improvement in the gun performance would further allow to extend the FEL to the 0.1 nm region. Such a system would produce radiation with a brightness many order of magnitude above that of any synchrotron radiation source, existing or under construction, with laser power in the multigigawatt region and subpicosecond pulse length.

## 1. Introduction

The progress in RF linacs and electron sources due to the recent work on linear colliders and FELs, makes now possible to combine these technologies to design and build a FEL in the soft X-ray region, capable of producing power in the GWatt range with subpicosecond pulses. Such a system, with a wavelength extending from 4nm down to 0.1 nm, thus covering the water window and the crystal structure region, offers unique and exciting new capabilities in areas as x-ray microscopy of biological samples, and holography of crystals.

In this paper we will first use a simple one dimensional FEL model to obtain and discuss the FEL scaling laws for the short wavelength region. Following the discussion of reference 1, we will show that for operation of an FEL at short wavelengths it is important to:

a. use an electron beam with small emittance and large longitudinal brilliance;

b. use a large beam energy, in the multi GeV region, to maximize the output radiation power;

c. use more focusing than that provided naturally by the undulator.

We will then apply these scaling laws to design a 4nm FEL working in the Self Amplified Spontaneous Emission mode of operation. We will then

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comment on the possibility of building this FEL using an existing RF photoinjector in S-band, like the one in operation at Brookhaven or under test at UCLA, a linac like the one in operation at SLAC, capable of reaching up to 50 GeV, and a bunch compression system, like the one already tested at SLAC.

We point out that all these systems exist and are in operation now with the required characteristics. An improvement in the RF photoinjector emittance by a factor of three, with no reduction in the longitudinal brightness, would also allow us to push the FEL operation down to the 0.1 nm region, with a beam in the 30 to 50 GeV energy region.

In all cases such an FEL operated to saturation in the SASE mode [1], will provide power in the multigigawatt range, with a pulse duration of about 0.2 picosecond. The radiation brightness of these sources exceeds by many order of magnitudes any synchrotron radiation light source, existing or under construction, providing of the order of $10^{14}$ photons/pulse in a diffraction limited angle, and with a bandwidth of $10^{-3}$.

This power can be farther increased by two order of magnitude if one is willing to add a tapered undulator, increasing the energy transfer efficiency from the electron beam to the radiation.

## 2. One Dimensional FEL Model

The basic problem of a X-ray FEL is the scaling of the gain with wavelength; as the wavelength becomes smaller the laser gain decreases. In addition the optical cavity used in a FEL oscillator becomes very lossy, because of the lack of good mirrors at wavelength below 100nm. To compensate for this effect one is forced to use electron beams with large peak current, and at the same time small emittance and energy spread. The road to a X-ray FEL requires the development of electron beams with unprecedented characteristics, as obtained recently with the development of high brightness sources, and the control of emittance dilution in RF linacs.

To obtain the FEL scaling laws we follow closely ref. (1), using a simple one dimensional model to describe the FEL physics in the high gain regime, which is the only one of interest for this application; effects like undulator imperfections will have to be included in a real design. The notations we use are: beam energy (units $mc^2$), $\gamma$; Beam particle density, $n$; radiation wavelength, $\lambda$; undulator period, $\lambda_u$; undulator field, $B_u$; undulator parameter, $K$; undulator frequency, $\omega_u = 2\pi/\lambda_u$; beam plasma frequency, $\Omega_p = (4\pi r_e c^2 n/\gamma)^{1/2}$. With these notations, and considering for simplicity a helical undulator, we can write the FEL synchronism condition as

$$\lambda = \lambda_u(1+K^2)/2\gamma^2 \qquad (1)$$

In the 1-D theory, and for a cold beam, the radiation field in the undulator grows exponentially until it saturates. Remarkably the exponential gain length, $L_G$, the saturation power, and all other important FEL characteristics are determined by one parameter [1,2], the FEL parameter introduced by Bonifacio, Narducci and Pellegrini,

$$\rho = \{(K/4\gamma)(\Omega_p/\omega_u)\}^{2/3} \tag{2}$$

The gain length is

$$L_G = \lambda_u/2\sqrt{3}\,\pi\rho \tag{3}$$

the laser power at saturation is related to the beam power, $P_B$, by

$$P_L = \rho\, P_B \tag{4}$$

and the saturation length is

$$L_S = \lambda_u/\rho \tag{5}$$

When we introduce effects like energy spread and 3-dimensional, diffraction effects, we can still use (3), (4) and (5) if some additional conditions are satisfied:

a) limit on beam fractional energy spread, $\sigma_\gamma = f_1\,\rho$, with $f_1 < 1$;

b) limit on beam emittance, $\varepsilon = f_2(\lambda/4\pi)$, with $f_2 < 1$;

c) condition for optical guiding, $Z_R = f_3 L_G$, with $f_3 > 1$;

where $Z_R = \pi\sigma_r^2/\lambda$, is the Raleigh range, and $\sigma_r$ is the rms radiation beam radius, which is of the same order of the electron beam radius. The gain length is a very important quantity; it determines the scale length over which effects have to occur to influence the exponential growth rate; all effects which take place over a distance larger than the gain length will have very little effect on the FEL performance.

One way to increase ρ, and decrease the gain length, is to strongly focus the beam through the undulator, reducing the betatron oscillation wavelength. This, however, can produce a reduction of the gain, because during an oscillation a particle changes its position and velocity, and as a result can get out of synchronism [3]. There is one remarkable case when this reduction does not occur, and that is when the betatron oscillation wavelength is that given by the transverse focusing produced by the undulator field only

$$\lambda_{\beta n} = \sqrt{2}\,\gamma\lambda_u/K \tag{6}$$

For the typical parameters of a X-ray FEL, with a large value of gamma, this quantity tends to be very large, tens or hundreds of meters, limiting the value of $\rho$. It is then convenient to introduce extra focusing to make the FEL parameter large, accepting at the same time some reduction in gain. This reduction is small if we satisfy the condition

d) condition for beam focusing $\lambda_\beta/2\pi = f_4 L_G$, with $f_4 > 1$,

so that the effect of betatron oscillations in a wavelength is negligible. It is important to notice that if conditions b, and c are satisfied than also the condition 'd' on the focusing is satisfied, since $\sigma_r^2 = \varepsilon\lambda_\beta/2\pi$; hence we will not consider 'd' as an independent condition.

All the basic physics described in these formulae, like exponential growth from noise or optical guiding, has been proved experimentally in the near or far infrared. Assuming that the same physics remain valid at shorter wavelength, we can use these formulae to design a soft X-ray FEL.

3. FEL Scaling Laws

In the design of a FEL we want to maximize $\rho$ for a given wavelength and beam characteristics. To this end we rewrite it using the beam invariants , $\varepsilon_N$ , $\varepsilon_L$ transverse and longitudinal normalized rms emittances (we assume for simplicity a cylindrically symmetric beam), and the longitudinal brilliance [1]

$$B_L = eNc/(\sqrt{2\pi}\,\varepsilon_L) = I_p/(\gamma\sigma_\gamma) \quad (7)$$

where $I_p$ is the peak current and $\sigma_\gamma$ is the relative rms energy spread. Using these quantities we obtain

$$\rho = \{(\lambda K/4\pi(1+K^2)\}^{2/3}\{4\pi\sigma_\gamma B_L/\lambda_\beta \varepsilon_N I_A\}^{1/3}\gamma \quad (8)$$

where $I_A = ec/r_e$ is the Alfven current. It is interesting to notice that the dependence of $\rho$ on $\lambda$ is not strong, so that a FEL at short wavelength seems feasible; in addition (8) shows that it is convenient to use a large beam energy. The cost of using a large beam energy is that, for the same wavelength, we have to increase the undulator period, and the undulator becomes longer. However, since $N_u \sim 1/\rho$ the undulator length increases only linearly with the beam energy.

If we use the conditions a,b,d we can also rewrite the FEL parameter as

$$\rho = \sqrt{3} f_1 K^2 B_L / 2 f_2 f_4 (1+K^2) I_A \quad (9)$$

For most cases this tells us that the order of magnitude of $\rho$ is simply the ratio of the longitudinal brightness to the Alfven current, showing the importance of achieving a large $B_L$ in the gun and accelerating system.

In figures 1 to 6 we also show the behavior of some characteristic FEL quantities vs electron energy for given radiation wavelength. The set of beam parameters used in these calculations are given in Table 1. The beam emittance and longitudinal brilliance are those that can be presently obtained from an RF photoinjector. We assume that after acceleration to an energy on the order of 1 GeV the beam is longitudinally compressed to reduce the bunch length to a subpicosecond value, and to increase the peak current by a factor of ten. Hence the peak current, pulse length and energy spread refer to the values after compression, at the undulator entrance.

Table 1: Input parameters for the calculations of figures 1 to 6.

| | |
|---|---|
| Normalized rms emittance, m | 2.5 10-6 |
| Longitudinal Brilliance, A | 10,000 |
| Peak current, A | 2,000 |
| Pulse duration, rms, ps | 0.16 |
| Relative energy spread, rms, % | 0.04 |

We also assume that during acceleration and compression the transverse emittance is not increased, and the final energy spread is determined by the longitudinal wakefields in the accelerating linac. This assumption is justified because the large peak current during acceleration goes together with a very short bunch length, strongly reducing the transverse wake fields.

## 3. A Soft X-Ray FEL

To design a FEL We have to maximize $\rho$, and at the same time satisfy the additional conditions a, b, c, d just discussed. In addition there is also another choice to be made for the FEL mode of operation. One possibility is to use an oscillator configuration, with an optical cavity, the other is to operate in the Self Amplified Spontaneous Emission (SASE) mode. The oscillator requires a smaller gain and a shorter undulator than SASE, if the optical cavity has small losses, and this condition is difficult to satisfy at short wavelength because also the best multilayered mirrors have reflectivity of about 50%, and they are easily damaged. This damage can be enhanced by the small laser spot size, and the corresponding high power density of the radiation. To increase the mirror reflectivity Newnam has suggested to use multifaceted metal mirrors operating by total external reflection. Another improvement can be made changing the optical cavity configuration from a two mirror design with near perpendicular angle of incidence, to a ring resonator with many mirrors and glazing angle of incidence.

The SASE avoids the mirrors and optical cavity problems, at the cost of using a longer undulator. In a SASE FEL one sends the electron beam through a long undulator; the spontaneous emission produced in the initial part of the undulator couples to the transverse particle velocity to modulate the electron energy on the scale of the radiation wavelength. This energy modulation leads to a bunching of the particles on the same scale length, and this bunching enhances the emission of radiation. It is clear that this process leads to an exponential growth of the radiation. This mechanism is similar to that of the negative mass instability in particle accelerators, although the radiation-beam coupling is with the transverse beam velocity instead of the longitudinal velocity. The radiation growth saturates when the electrons are trapped in the potential well formed by the combined action of the radiation and undulator field (ponderomotive potential well).

Using the one dimensional model discussed before, we can design a Soft X-ray FEL based on SASE. An example of such a system is given in Table 2, using the parameters of Table 1. The beam energy for this example has been selected from fig. 4, to be the point where the Gain length is about twice the Raleigh range.

TABLE 2: Example of a 4nm FEL

| | |
|---|---|
| Electron energy, GeV | 6 |
| Undulator period, cm | 6.8 |
| Undulator field, T | 0.63 |
| Betatron Wavelength, m | 10 |
| FEL Parameter | 0.002 |
| Gain length, m | 3.2 |
| Raleigh range, m | 1.6 |
| Pulse length, rms, ps | 0.16 |
| Undulator saturation length, m | 34 |
| FEL Power, GW | 24 |

4. Results of Numerical Simulations

Although the 1-D model is a useful guide to the FEL design, to obtain more detailed prediction of the system performance one needs to evaluate self consistently the effects of diffraction, energy spread, and additional focusing. This can be done using numerical codes. We have used the code developed by I. Ben Zvi and L. H. Yu [4], to study the dependence on energy and on external focusing, for a planar undulator.

In Table 3 we show a study of a 4 nm FEL based on the beam parameters given in Table 1. The first five rows show the dependence on energy for fixed betatron wavelength, showing that using larger energy and longer undulator periods leads to a larger FEL parameter and FEL power, at a cost of a longer undulator. The last two rows show the importance of the external focusing, by increasing the betatron wavelength to 100m, or to the natural value of 508 m.

The case of a 0.1 nm FEL is shown in Table 5. For this case the beam energy has been kept at the maximum energy of the SLAC linac, 50 GeV. We assume that this high energy will permit a second compression stage to raise the peak current to 5 kA, reducing the pulse length to about 80 femtosecond. We have also to assume that the transverse normalized rms emittance is now 1 mm mrad, above the present state of the art, but a value that should be reached in the near future.

Table 3: 4 nm FELs

| E, GeV | $\lambda_u$, cm | $B_u$, T | $\lambda_\beta$, m | $\rho$, x$10^{-3}$ | $L_G$, m | $Z_R$, m | $P_L$, GW |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 0.86 | 30 | 2 | 3.6 | 0.9 | 6.3 |
| 7.5 | 8 | 0.86 | 30 | 1.86 | 2.9 | 1.3 | 5.8 |
| 5 | 6 | 0.86 | 30 | 1.7 | 2.3 | 1.9 | 4.2 |
| 2.8 | 4 | 0.86 | 30 | 1.5 | 1.7 | 3.4 | 2 |
| 1.2 | 2 | 0.86 | 30 | 1.1 | 1.3 | 7.8 | 0.44 |
| 10 | 10 | 0.86 | 100 | 1.3 | 5.3 | 3.1 | 4.6 |
| 10 | 10 | 0.86 | 508 | 0.78 | 9.9 | 15.6 | 1.8 |

Table 5 shows the FEL performance when changing the additional focusing; in this case the natural undulator focusing is about 2,000 m. One can see that the performance drops dramatically for a betatron wavelength longer than 300 m, because of the decrease in beam density, or shorter than 100 m, because of diffraction effects, with an optimum at about 100 m.

Table 5: The 0.1 nm FEL

| E, GeV | $\lambda_u$, cm | $B_u$, T | $\lambda_\beta$, m | $\rho$, x$10^{-3}$ | $L_G$, m | $Z_R$, m | $P_L$, GW |
|---|---|---|---|---|---|---|---|
| 50 | 10 | 0.7 | 10 | 1.5 | 35 | 0.9 | 0.01 |
| 50 | 10 | 0.7 | 30 | 1 | 13 | 2.8 | 3 |
| 50 | 10 | 0.7 | 100 | 0.7 | 13 | 9.5 | 9.7 |
| 50 | 10 | 0.7 | 300 | 0.5 | 22 | 28 | 3.6 |
| 50 | 10 | 0.7 | 1,000 | 0.33 | 66 | 95 | 0.15 |
| 50 | 10 | 0.7 | 2,000 | 0.26 | 175 | 189 | 0.01 |

## 5. Conclusions

We have shown that using existing electron gun technology and the SLAC linac one can build today a FEL in the water window, at about 4 nm. An improvement in the gun emittance by a factor of three for the same longitudinal brilliance, would allow the extension of the system to 0.1 nm. In both cases the radiation brightness far exceeds any other source existing or under construction, and would open a completely new region of experimentation.

While the addition of an RF photoinjector to the SLAC linac is a relatively minor project, the undulator required for these FELs is long, from about 30 m for the 4 nm case, to about 100 m for the 0.1 nm case. The effect of undulator errors has still to be evaluated; it is important to remember that also the undulator error and their effects must be evaluated only over a gain length, thus reducing the problem to a more manageable size. Based on our experience on existing undulator we have no reasons to believe that required tolerances will be met. Methods to reduce the undulator length using a High Gain Optical Klystron have also been suggested [5] and should be considered to reduce the cost of the system.

In the present work we have not attempted to optimize the system, but only to show that the presently available technology makes such an FEL feasible. Further work is needed to optimize the system design, in particular parameters like the undulator field, the added external focusing and tolerances, including consideration of low field undulators with added focussing function [6].

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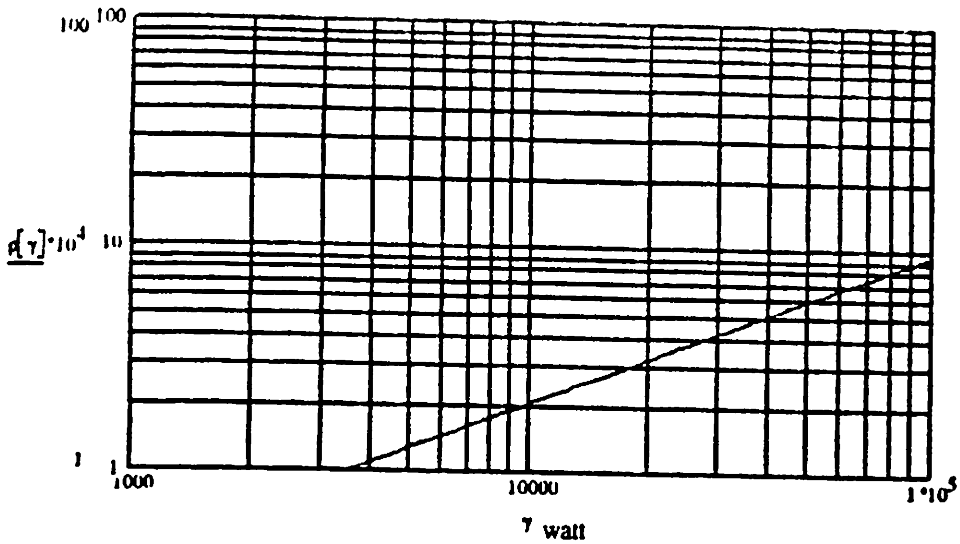


Fig.1 FEL parameter vs electron energy.

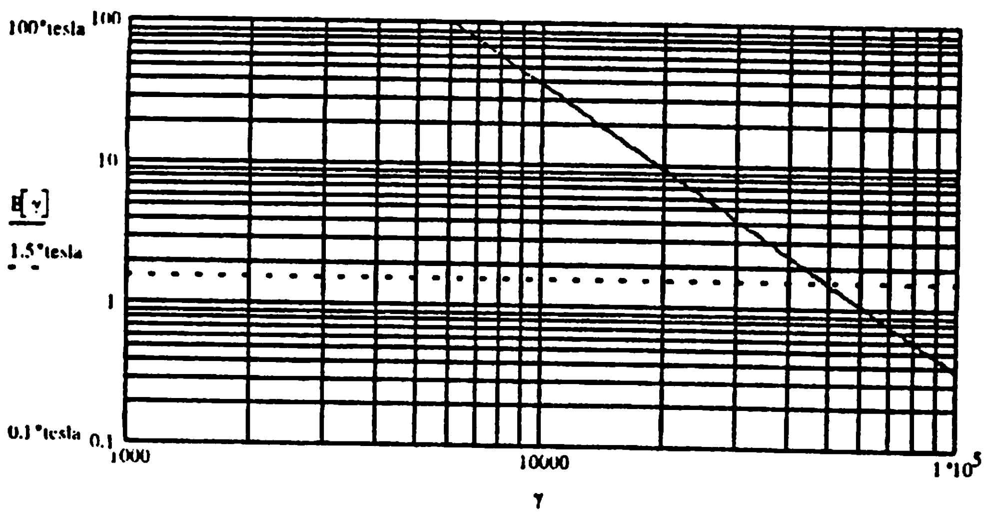


Fig.2 Undulator magnetic field vs electron energy

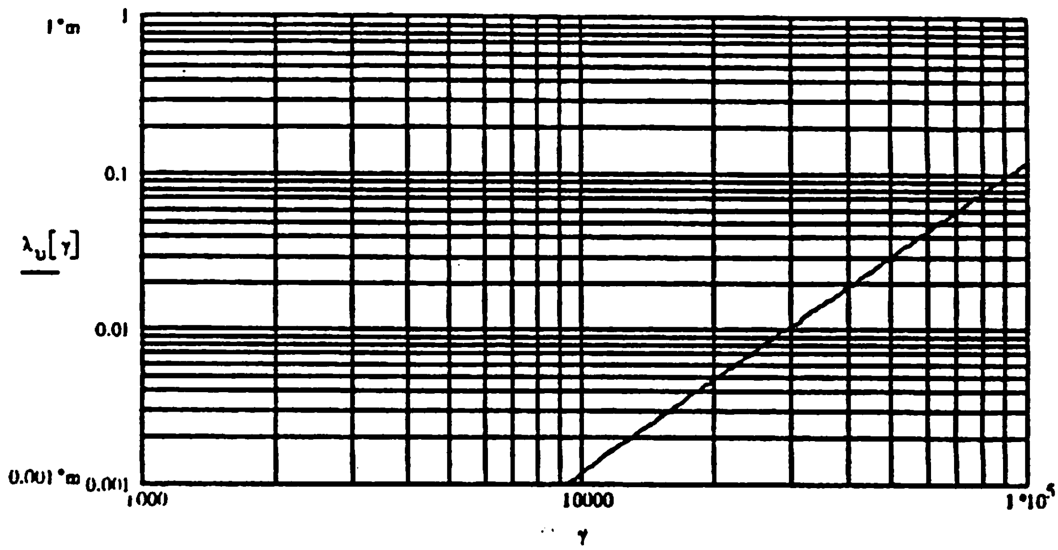


Fig. 3  Undulator period vs electron energy.

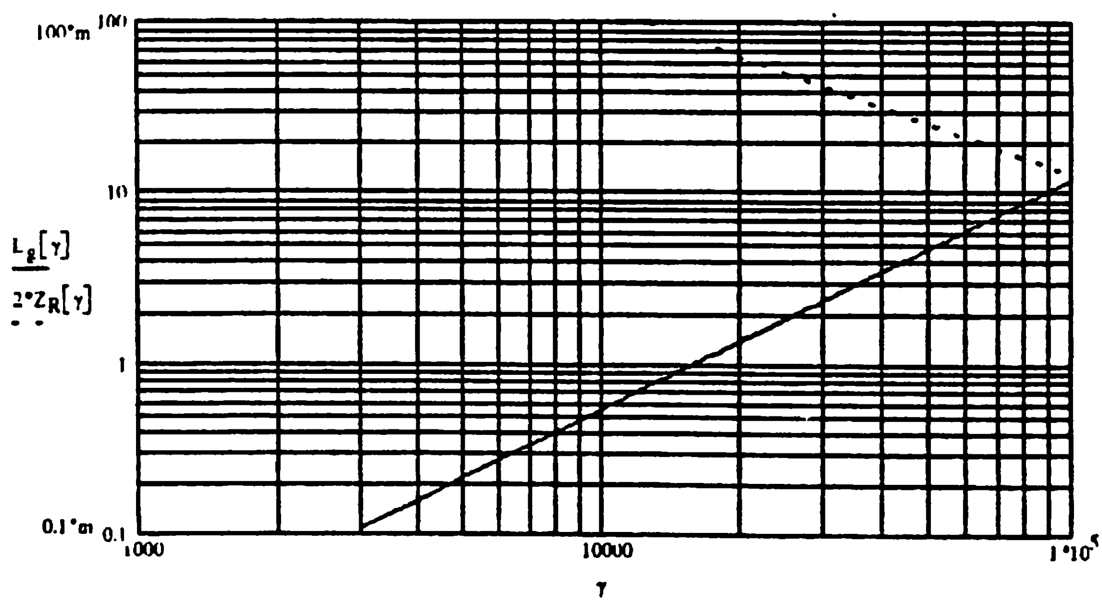


Fig. 4 Gain length and Raleigh range vs electron energy.

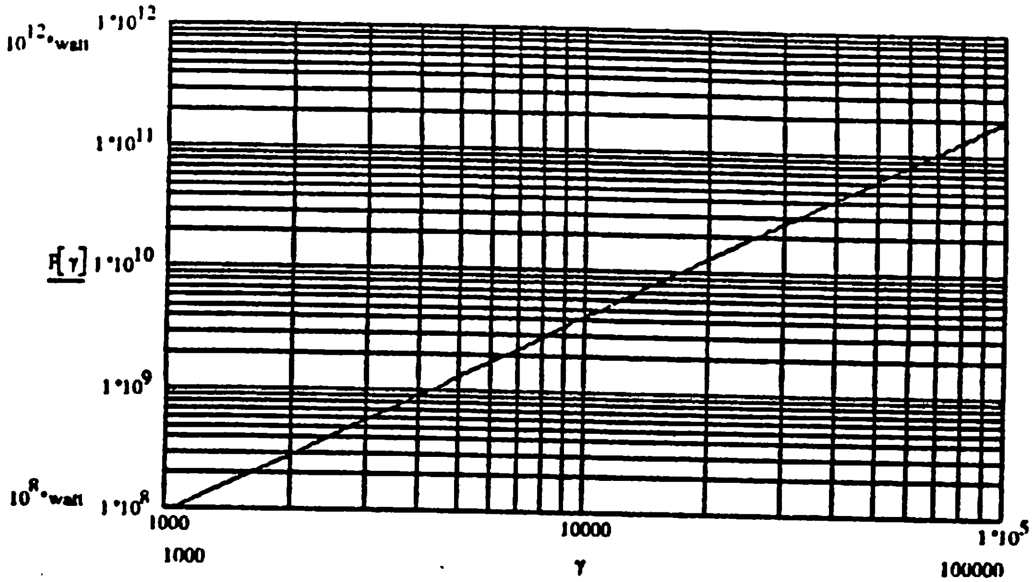


Fig. 5 FEL power vs electron energy.

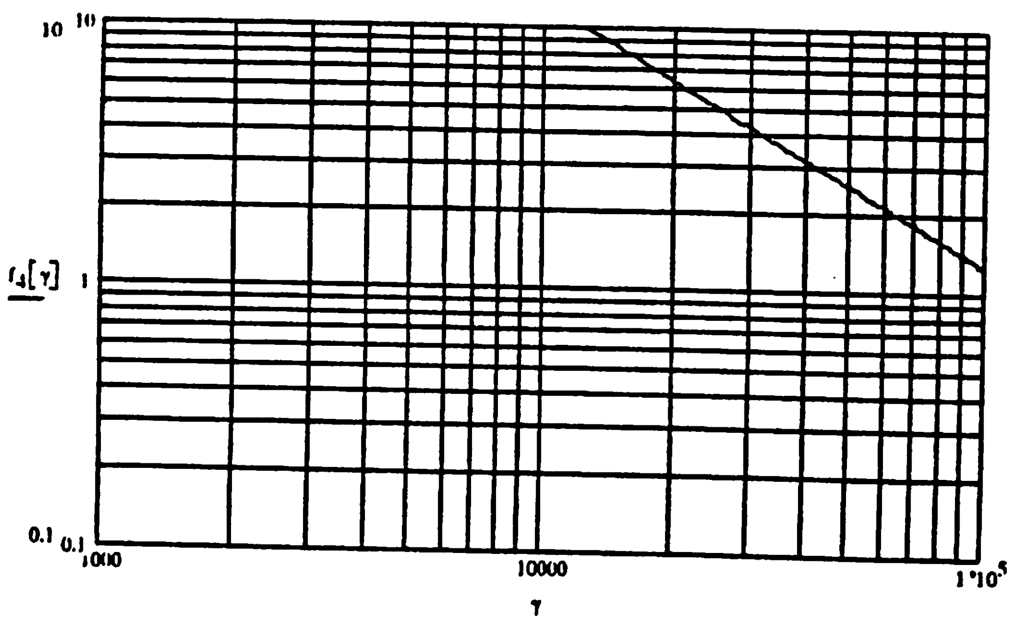


Fig. 6 Ratio of emittance to wavelength vs electron energy.