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Using The SLAC Two-Mile Accelerator For Powering An FEL*

William A. Barletta[1], Andrew M. Sessler[2]

and

Li-Hua Yu[3]

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A parameter survey is made, employing the recently developed 2D formalism for an FEL, of the characteristics of an FEL using the SLAC accelerator. Attention is focused upon a wavelength of 40 Å (the water window) and a 1 Å case is also presented. We consider employing the SLAC linac with its present operating parameters and with improved parameters such as would be supplied by a new photo-cathode injector. We find that improved parameters are necessary, but that the parameters presently achieved with present-day photo-cathode guns are adequate to reach the water window.

1 Lawrence Livermore National Laboratory, Livermore, CA 94550.
2 Lawrence Berkeley National Laboratory, Berkeley, Ca 94720.
3 Brookhaven National Laboratory, Upton, NY 11973.

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Introduction

The use of SLAC for powering an FEL has been suggested by a number of people through the years and at this workshop with details by Claudio Pellegrini.[1] His work has stimulated the present study. As a result, we have attained a new level of understanding of FEL parameter space and, in particular, have arrived at parameters for SLAC which may be of general interest.

Our analysis is based upon the analytic 2D work by Yu, Krinsky and Gluckstern and by Chin, Kim, and Ming.[2,3] This work has been compared with the large numerical simulation codes FRED and FELIX and shown to agree with them to within a few percent.

A simple 1D analysis, with careful attention to the constraints that limit the validity of 1D theory has been given by Barletta and Sessler.[4] In particular, they introduce three parameters, f_1, f_2, and f_3, which characterize the validity of a 1D analysis. These parameters are:

$$f_1 = \varepsilon_n/\gamma(\lambda/2\pi),$$

$$f_2 = 2\,\varepsilon_n^2/\rho[r_b^2(1+a_w^2)],$$

$$f_3 = L_G/Z_R,$$

where all the symbols are obvious (and are defined in Ref 4). Beam emittance and radius are the rms values. Validity of the 1D theory requires that the f-factors be less than or equal to unity. We note that $f_2 = f_1^2 f_3$ so the three criteria are not independent (although the physical arguments from which they are derived seem different).

We will see that the 1D analysis is quite adequate for study of an FEL at SLAC. That is, the 2D effects are generally "bad" (increasing the gain length and extraction efficiency) and a "good FEL" is one that operates in a regime where the 1D theory is valid. Thus the design of a device can simply proceed by use of the 1D theory and by making the f-factors close to unity (f-factors less than unity give a device that is less than optimal). That is, one simply increases the beam energy until the f_1 criterion is satisfied, and then increases focusing (either by external magnets or ions) until the f_3 criterion is met. When we increase focusing, we ignore, in computing FEL properties, the effect of the additional focusing on the longitudinal motion of electrons. We expect this approximation to be quite valid.

Parameter Search

1. Present SLAC characteristics

We take as the parameters of the SLAC linac the following:

$$(\Delta E/E) = 10^{-2}/E \text{ (head-to-tail)},$$
$$(\Delta E/E) \approx 10^{-4}, \text{ (instantaneous)}$$
$$I = 2.5 \text{ kA},$$
$$\varepsilon_n = 25\pi \times 10^{-6} \text{ m}.$$

With regard to FEL performance the instantaneous spread is most important. Using these values we tried to design an FEL at 40 Å. Although we did not make an exhaustive search, the results at 20 GeV are close to optimal with respect to minimizing the length of wiggler to reach saturation. Using the instantaneous energy spread we have

$$\lambda_w = 9.9 \text{ cm},$$
$$B = 1.7 \text{ T},$$
$$\rho = 5.63 \times 10^{-4},$$
$$f_1 = 1.0,$$
$$f_2 = 0.36,$$
$$f_3 = 0.36,$$
$$r_b = 220 \text{ mm},$$
$$Z_R = 39 \text{ m},$$
$$L_G = 14.2 \text{ m}.$$

The last is the gain length for the power, and it is clearly too long for a practical FEL. Additional focusing, such as would be provided by the ions in an underdense plasma, doesn't serve to reduce the gain length.

2. Improved Normalized Emittance

It is clear that the energy of the electron beam must be chosen high enough to satisfy the f_1 condition (but shouldn't be taken any higher than necessary because the gain length scales linearly with energy). Reduction of the beam emittance allows one to operate at a lower beam energy. Consequently the gain length will be reduced. We consider the case where

$$\varepsilon_n = 5\pi \times 10^{-6} \text{ m}.$$

Such emittances have been obtained with photo-cathode guns.

Taking the $\Delta E/E$ and current as before, we have the seven cases of Tables 1a and 1b. In Table 1a the calculation is based on the instantaneous energy spread whereas Table 1b uses the head-to-tail value. The first two cases have an energy of 40 GeV. The second case is with focusing increased over the natural wiggler focusing. Cases 3 and 4 are at 20 GeV for natural focusing and with extra focusing. One can see that performance is better than at 40 GeV. Cases 5 and 6 are at 10 GeV, and again the situation has improved. Finally, Case 7 is at only 2 GeV. The performance is now quite acceptable if the energy spread can be made small compared to ρ, wheras for a spread of 0.5% the performance is poor. One can see immediately, by examining the f-factors, the trends in energy. For example, we can say that in cases 1 and 2 the emittance is too good. Too good in the sense that increasing the emittance by lowering the beam energy would improve performance.

3. Very Much Improved Normalized Emittance

A further decrease of normalized emittance will improve the FEL performance even more. Taking

$$\varepsilon_n = 2.5\pi \times 10^{-6}\ \text{m}$$

and keeping $\Delta E/E < 5 \times 10^{-4}$, we obtain the two cases shown in Table 2 at 40 Å. One can see that the either case (without and with extra focusing) yields parameters of considerable interest.

In order to reach a wavelength of 1 Å requires an even smaller normalized emittance and a larger peak current. Taking

$$\varepsilon_n = 1 \times 10^{-6}\ \text{meters},$$
$$I = 5\ \text{kA},$$
$$(\Delta E/E) = 10^{-4},$$

we obtain:

$$\lambda_w = 4\ \text{cm},$$
$$B = 1.71\ \text{T},$$
$$\rho = 3.8 \times 10^{-4},$$
$$r_b = 45\ \text{mm},$$
$$Z_R = 63\ \text{m},$$
$$L_G = 7.99\ \text{m},$$

which is of marginal practicality (for the wiggler is long and field errors must be kept below a tight tolerance), but possible. Allowing for extra focusing (the factor f_3 is only 0.13) reduces the Rayleigh Length and brings gain length to L_G = 4.8 m.

Conclusions

There are a number of insights we can draw from this study:

1. The first is a purely technical point having to do with FEL design. We have re-affirmed that the 1D theory is adequate to select the characteristics of practical (non-marginal) FELs. One simply increases the beam energy until the f_1 criterion is satisfied, and then increases focusing (either by external magnets or ions) until the f_3 criterion is met.

2. SLAC, with its present parameters, is not able to be used as a driver for an interesting (less than 40 Å) FEL.

3. Equipping SLAC with a photo-cathode gun and by-passing the damping rings allows one to produce low emittance and to keep energy spread small. In this case one can use a small portion of the linac to drive an interesting FEL.

4. If the gun normalized emittance is less than $5\pi \times 10^{-6}$ meters and if the energy spread is small, then an FEL in the water window only requires an electron beam energy of 2 GeV. This could be done with the last one or two sections of SLAC (leaving the first 28 sectors for other purposes such as injecting into PEP II).

5. If SLAC performance can be so increased as to achieve, at a final energy of 32 GeV, a beam of 5 kA having an energy spread $(\Delta E/E) = 4.4 \times 10^{-5}$ and an emittance normalized $\varepsilon_n = 1 \times 10^{-6}$ meters, then a 1 Å FEL can probably be constructed. For this case one would have to make a 3-D analysis of the effects of field tolerances and alignment errors to make a final decision on practicality.

6. Finally, we note that in all cases we are limited by beam normalized emittance and, consequently, beam conditioning will have important benefits.[5] In particular, conditioning will allow construction of FEL, with wavelengths of 40 Å or less, with drivers having energies of only (about) 1 GeV, and therefore not require high-energy particle beams.

References

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Table Ia.

Design of a 40 Å FEL Employing SLAC with $\varepsilon_n = 5\pi \times 10^{-6}$ m, I = 2.5 kA.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
E (GeV)	40	40	20	20	10	10	2
$\Delta E/E \times 10^4$	1	1	1	1	1	1	1
λ_w(cm)	18	18	9.9	9.9	6.0	6.0	3.0
ρ	7.0×10^{-4}	3.2×10^{-3}	7.7×10^{-4}	2.1×10^{-3}	8.3×10^{-4}	1.8×10^{-3}	8.8×10^{-4}
Z_R (m)	9.7	0.19	7.9	.78	7.5	1.1	15
a_b (μm)	110	16	100	32	98	38	140
focusing	natural	extra	natural	extra	natural	extra	natural
λ_β (m)	120.	24.	490.	35	230	35	95
f_1	0.1	0.1	0.2	0.2	0.4	0.4	2.01
f_2	.02	0.23	0.04	0.24	0.10	0.35	0.57
f_3	1.62	41.6	0.95	8.08	0.56	2.60	0.17
L_G (m)	15.6	8.0	7.52	4.46	4.17	2.9	2.5

Table Ib

Design of a 40 Å FEL employing SLAC with $\varepsilon_n = 5\pi \times 10^{-6}$ m, I = 2.5 kA.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
E (GeV)	40	40	20	20	10	10	2
$\Delta E/E \times 10^4$	2.5	2.5	5	5	10	10	50
λ_w(cm)	18	18	9.9	9.9	6.0	6.0	3.0
ρ	7.0×10^{-4}	3.2×10^{-3}	7.7×10^{-4}	2.1×10^{-3}	8.3×10^{-4}	1.8×10^{-3}	8.8×10^{-4}
Z_R (m)	9.7	0.10	7.9	0.78	7.5	1.1	15
a_b (μm)	110	11	100	32	98	38	140
focusing	natural	extra	natural	extra	natural	extra	natural
λ_β (m)	120.	24.	490.	35	230	35	95
f_1	0.1	0.1	0.2	0.2	0.4	0.4	2.01
f_2	.02	0.46	0.04	0.24	0.10	0.57	0.72
f_3	1.24	26.8	0.76	5.6	0.45	2.1	0.10
L_G (m)	19.2	8.2	13.4	5.1	20.5	4.8	>100

Table II.

A 40 Å FEL driven by a beam with $\varepsilon_n = 2.5\pi \times 10^{-6}$ m and peak current 2.5 kA.

	Case 1	Case 2
E (GeV)	2.0	2.0
$\Delta E/E$	5×10^{-4}	5×10^{-4}
λ_w(cm)	3.0	3.0
ρ	1.1×10^{-3}	1.65×10^{-3}
Z_R (m)	7.5	2.2
a_b (μm)	98	54
λ_β (m)	95	28
f_1	1.0	1.0
f_2	0.29	0.64
f_3	0.17	0.37
L_G (m)	2.01	1.46