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Linacs for Free Electron Lasers

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Abstract

In this paper we discuss the use of a RF linac as a FEL driver. We first review the basic FEL physics and discuss the beam characteristics needed for a good FEL driver. We then compare these requirements with the present state of the art in RF linacs, and discuss some possible R&D lines.

Introduction

The interest in Free electron Laser is due to: its large wavelength range, which at present extends from about one centimeter to 0.24 micrometer; its tunability; its high peak power, ranging up to the GW level. Because of its flexibility the FEL can find applications in many areas, such as particle acceleration, heating of fusion plasmas, material sciences, biological, medical and solid state research. A review of the FEL operation and experiments can be found in reference 1, and in a recent paper by Roberson and Sprangle[2].

There are two main wavelength regions of interest for FELs applications, where they can be superior to other sources: one is the IR and millimeter to centimeter region; the second is the short wavelength region, below 0.1 micrometer. The first has been widely explored; many systems are in operation at these wavelengths in several laboratories. The second is the new frontier for FELs; its development requires electron beams with a six dimensional phase space density larger than that available today.

FELs use different types of electron accelerators, from induction linac to storage rings, depending on the radiation wavelength required, the beam energy and pulse duration. The RF linac can provide high quality beams of energies from a few MeV to Gev, to drive FEL in the infrared, visible or UV spectral regions. They could also be used in the future as drivers for Soft X-ray FELs. The short pulse duration, from picoseconds to tens of picoseconds, is a desirable property for many research applications, although it limits the operation at wavelength shorter than about 50 μm because of the slippage.

The Stanford superconducting RF linac was the accelerator used for the first FEL in 1976-77[3,4], and is still being used now by a Stanford-TRW group. This group has reported the operation of the first visible FEL, with a power of 21 KW at 0.52 μm[5]. Room temperature linacs have been used in the following years at Stanford[6,7,8], Los Alamos[9,10], Boeing[11] to drive FELs from 35 μm to the visible, with peak powers up to 40 MW, and pulse length as short as one picosecond. Both oscillators and master oscillator power amplifier [12] configurations have been used. Optical guiding, sidebands and harmonic generation have been observed.

Basic FEL Physics

To describe the basic FEL physics we use a model based on the 1-D theory[13,14], in which we include effects like diffraction, beam energy spread and optical guiding; other effects, as for instance undulator imperfections, are not and will have to be considered in a real design. The notations we use are those of reference[15] and are: beam energy (units mc^2), γ; particle density, n_e; radiation wavelength, λ; undulator period, λ_u; undulator field, B_u; undulator parameter, $K = eB_u\lambda_u/2\pi mc^2$; undulator frequency, $\omega_0 = 2\pi c/\lambda_u$; beam plasma frequency $\Omega_p = (4\pi r_e c^2 n_e/\gamma)^{1/2}$.

With these notations, and considering for simplicity a helical undulator, we can write the FEL synchronism condition as

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

In the 1-D FEL theory , and for a cold beam, the radiation field in the undulator grows exponentially until it saturates; the exponential gain length, L_G, and the saturation power are determined by one parameter[13,15],

$$\rho = \left(\frac{K}{4\gamma}\frac{\Omega_p}{\omega_0}\right)^{2/3} \tag{2}$$

The gain length is

$$L_G = \frac{\lambda_u}{2(3)^{(1/2)}\pi\rho} \tag{3}$$

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the laser power at saturation is related to the beam power, P_L, by

$$P_L \sim \rho P_{beam} \tag{4}$$

and the saturation length is

$$L_s \cong \frac{\lambda_u}{\rho} \tag{5}$$

When the gain length is shorter than the undulator length it is convenient to use the Small Signal Gain, G, to characterize the FEL. This quantity can also be expressed in terms of ρ [13]

$$G = \frac{1}{2}(4\pi\rho N_u)^3 f(4\pi N_u \Delta) \tag{6}$$

where N_u is the number of undulator periods, Δ is the "detuning", i.e. the relative difference between the resonant and the actual beam energy, and $f(x) = (1 - \cos x - (x/2)\sin x)/(x/2)^3$ is a function with a maximum value of about 0.6.

The gain and the gain length are reduced, by effects like energy spread, diffraction effects, and by how much we focus the beam through the undulator. This reduction is small if some additional beam conditions are satisfied:

a) limit on energy spread: $\sigma_e < \rho$;

b) limit on emittance: $\epsilon < \frac{\lambda}{2\pi}$;

c) optical guiding: $\frac{Z_R}{L_G} > 1$;

where $Z_R = \pi\sigma_r^2/\lambda$, is the Rayleigh range, σ_r the beam radius, and σ_E the relative energy spread. The gain length is a very important quantity: all effects which take place over a distance larger than the gain length will have 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. This, however, can produce a reduction of the gain[16], except when the betatron oscillation wavelength, is that given by the transverse focusing produced by the undulator field,

$$\lambda_\beta = \frac{2^{1/2}\gamma\lambda_u}{K} \tag{7}$$

This reduction is small if we focus to a betatron wavelength smaller than (7) but larger than the gain length. The additional focusing can be obtained with external focusing elements, like quadrupoles[15], or, as proposed by Barletta and Sessler[17], with ion focusing.

The FEL wavelength is defined by (1), hence by the beam energy. The minimum linewidth is given by the inverse of the number of wavelength in a bunch length. For most application it is important to achieve this linewidth and keep the wavelength stable within the linewidth; this requires for the beam energy fluctuation $\Delta\gamma/\gamma < \Delta\lambda/2\lambda$.

FEL Scaling Laws

In the design of a FEL we maximize ρ for a given wavelength and beam characteristics. To this end we rewrite it using the beam invariants ϵ_N, transverse normalized rms emittance (we assume for simplicity a cylindrically symmetric beam), the longitudinal brilliance[14,15], and the charge per bunch eN, as

$$B_L = \frac{eNc}{(2\pi)^{1/2}\epsilon_L} \tag{8}$$

Using these quantities and condition "a" to write $\sigma_e = \eta\rho$, we obtain

$$\rho = \frac{\lambda}{4\pi}\frac{K}{1+K^2}\left(\frac{4\pi B_L \eta}{\lambda_\beta \epsilon_N I_A}\right)^{1/2} \gamma^{3/2} \tag{9}$$

where $I_A = ec/r_e$.

It is interesting to notice that the dependence of ρ on λ is not too strong, so that a FEL at short wavelength seems feasible; in addition (11) shows that it is convenient to use a large beam energy.

The value of the FEL parameter depends now on very few beam related quantities, the energy and the beam invariants, and is thus well suited for a discussion of the accelerator driving the FEL.

As an example we consider now a FEL operating in the Soft X-ray wavelength. A possible set of parameters can be obtained from the model discussed above and is given in Table 1. This FEL can be operated in an oscillator configuration, with an optical cavity[19], or in the Self Amplified Spontaneous Emission (SASE) mode[20]; a discussion and comparison of the two modes can be found for instance in reference[19,20].

The combination of small emittance and large longitudinal brilliance given in Table 1 is not obtainable today, and using existing accelerators one can only produce FEL radiation in the visible or near UV. Several groups are working to produce beams with the characteristics similar to that of Table 1, following two routes: storage rings at Duke and Dortmund University; linacs at Los Alamos, Brookhaven and UCLA. These have been reviewed at a Workshop held at Brookhaven in 1987[21]. In the following section we will discuss the RF linac approach.

TABLE 1.

Example of Soft X-ray FEL

Wavelength, nm	5
Normalized emittance (rms), mm mrad	1
Electron energy, GeV	1.0
Longitudinal Brilliance, A	5000
Energy spread, %	0.1
Peak current, A	600
λ_β, m	3.3
ρ	0.0024
Undulator Period, cm	2
Gain Length, m	1.8
Rayleigh Length, m	1.7
Beam Power, GW	600
Laser Power, GW	1.4

The Linac

In this section we want to discuss the main characteristics of the beam produced by RF linacs. We will start with a discussion of the electron source and its limitation and will continue with the main accelerator.

The Electron Gun

The electron gun for an FEL driver linac is of very great importance. It must produce a beam with high peak current and small emittance and energy spread, with all these conditions being met simultaneously. The minimum normalized, rms emittance for a gun with a circular cathode of radius a and temperature T, neglecting space-charge and other effects like non-linear and time dependent forces, is

$$\epsilon_N = \frac{a}{2}\left(\frac{kT}{mc^2}\right)^{1/2} \qquad (10)$$

where the temperature is related to the transverse electron momentum, p_T, by $kT \approx p_T/2m$. The cathode radius is defined by the total current, I, that we need and the current density J; we can rewrite

$$\epsilon = \{(kT/mc^2)(I/4\pi J)\}^{1/2} \qquad (11)$$

For a thermionic cathode the current density is lower than about 40 A/cm^2, and kT is about 1 eV, leading to a normalized emittance of $0.6(I(A))^{1/2}$ mm mrad. For a photocathode one can have kT about 0.2 eV and a current density of about 1000 A/cm^2 or larger, leading to an emittance of about $0.055\ (I(A))^{1/2}$ mm mrad.

Space-charge and non-linear effects will substantially increase this values of the emittance, and much work has been done to minimize this blow-up. There are two main ways to approach the problem: DC or pulsed guns, followed by a bunching/compression system to produce high peak current and match the beam to the linac; RF guns, with the cathode inside a high field cavity and fast initial acceleration. In both ways one can produce peak currents of about 100 A or larger and emittances of about 10 mm mrad.

In the case of DC or pulsed cathodes one needs to bunch the beam using one or more bunching cavities, to produce the bunch length needed for subsequent acceleration in the linac, and the peak current in the 100 A range needed for the FEL gain. During this process the emittance increases substantially.

A recent design of an IR FEL driver at LBL[22] consists of a 100 KV gun producing a peak current of 2.5 A for 1 ns, followed by two bunching cavities at 146 and 511 MHz and one bunching L-band standing wave structure. The beam energy at the system exit is about 6 Mev, with a peak current of about 100 A, pulse duration of 10 ps, normalized rms emittance of 10 to 20 mm mrad, energy spread less than 0.5 %.The longitudinal brilliance is about 400 A.

In the case of RF guns[23,24,25] one can use either thermoionic cathodes or photocathodes. The space charge effects are reduced by applying large electric fields on the cathode surface, of the order of 50 to 100 MV/m, so that the electrons become relativistic in a distance from the cathode of the order of one centimeter. The best results have been obtained with photocathodes, at the cost of adding to the system a high power laser. In this case the beam is bunched by the laser pulse at the cathode, phased to produce electrons only when they are accelerated, and one can use the large current density to produce high peak current with a small cathode radius. For thermoionic cathodes the current is mainly limited by the heating of the cathode due to the backstreaming electrons.

As an example, the Los Alamos gun, operating at about 1.3 GHz, with a Cs_3Sb cathode, and a field on it of 60 MV/m, has produced a beam with a normalized rms emittance of about 10 mm mrad, and a longitudinal brilliance of 2000A[26].

The limitations on the beam emittance produced by a RF gun have been analyzed(27); the main effects are: space charge, non linear and time dependent RF fields, cathode temperature and current density. For present systems the main contribution to the emittance is produced by space charge effects near the cathode, which depends on the longitudinal charge density, and makes it vary from the center to the tails of the bunch. This effect can be at least partly controlled by increasing the accelerating field, or shaping the laser pulse, to produce a step like density distribution, or by selecting the core of the bunch out of a longer one, or by introducing non-linear or time dependent focusing elements(28). Similar limitations apply to the buncher section when using a thermionic low voltage gun. We expect that using these techniques we will able in the future to produce a beam as given in Table 1.

Beam Loading and Fluctuations.

To maintain the FEL wavelength and intensity within the limits required for many applications we must impose stringent tolerances on the beam energy and intensity, in addition to those on the emittance, energy spread, and peak current. There are two main type of effects which can change the beam characteristics during acceleration. Fluctuations in RF voltage and phase and in beam intensity can produce a bunch to bunch energy deviation. Wakefields induced by the beam can produce energy spread and emittance blowup within a bunch and multibunch effects (beam breakup).

The fluctuation in the beam energy must be limited to a value smaller than the energy spread, which we expect to be of the order of a few tenth of a percent. In addition, for a FEL oscillator we must control the arrival time of the bunches to the undulator to a fraction of the bunch length.

Klystron voltage fluctuations produce both a field and a phase fluctuation thus changing the output beam energy. These effects can be reduced by passive regulation in the modulator to about 0.5%. For further improvements one can use feed-back control. For pulses longer than the filling time, one can use feedback during the macropulse; for shorter pulses one can use a feedback system from pulse to pulse. For CW or almost CW operation, like one can have in a superconducting linac, it is possible to have better reproducibility of the beam characteristics. In the Stanford superconducting linac the total time averaged energy spread is less than 0.1%. Similar or better results can also be obtained in a race track microtron.

Fluctuations in the bunch arrival time must also be controlled to picosecond or sub picosecond level. In the case of a laser-gun this means also to control the time of arrival of the laser pulse on the cathode, using a single master oscillator for the RF system and the mode-locked laser.

For large average current and long pulses the beam break-up effect is a concern. Several techniques have been developed to control this effect, like increasing the accelerating gradient, reducing the higher mode impedance, and staggering the tune of the dangerous modes.

At the other extreme of a FEL operating as an amplifier or in the SASE mode, only one electron bunch is needed in a macropulse. In this case effects like the ripple of the klystron output are less important as long as the bunch is synchronized to the trigger system, and what matters is only the reproducibility of the RF waveform from pulse to pulse. Also in this case we expect to be able to have the bunch energy reproducible to about 0.1%.

For high gain, high peak current system wakefields become the dominant effect; the longitudinal wakefield can produce an energy spread and the transverse wakefield can blow-up the transverse emittance(29). For a single bunch the energy variation along its length due to the longitudinal wakefield can be partly compensated using the sinusoidal form of the accelerating field. The compensation however cannot be perfect and a residual energy spread will remain. For bunch currents in the 100A region and an S-band linac this residue can be of the order of 0.2%. The wake field effects depend strongly on the linac RF frequency. The longitudinal wakefield scales like the inverse square of the wavelength and the transverse like the inverse cube. This favors low frequency linacs, where also the multibunch beam loading can be smaller because of the larger energy stored in the cavities, for the same accelerating field. Transverse wake field effects can be controlled using the BNS damping(30), i.e. introducing a controlled energy spread in the bunch and removing it at the linac output.

To reduce the effect of wakefields on a single bunch and achieve a large peak current and a small energy spread we can use the bunch compression technique at several stages during the acceleration process. For the example of Table 1 we assumed $\epsilon_L = 2.10^{-5}$ m at 5 MeV, corresponding to a charge in the bunch of 1 nC, a 0.3 % energy spread and a rms bunch length of 0.6 mm; at 100 MeV we assume that the emittance is $2.4.10^{-4}$, for an energy spread of 0.2%, determined by beam loading, and the same pulse length; at this energy we can compress the bunch increasing the energy spread by 3 and reducing the pulse length to 0.2 mm; subsequent acceleration to 1 GeV would reduce the energy spread to less than 0.1%; in effect the energy spread is determined again by beam loading, and for this very short bunch length we expect this to remain at 0.1%. Using this beam manipulation the final peak current is 600 A, a value consistent with results obtained in the SLC at SLAC, where the peak current is 400 A with an energy spread of 0.1%.

Conclusions

The RF linac is the driver of choice for the infrared to visible wavelength region. Compact high gradient linacs and RF guns now being developed can reduce the FEL cost and make it more attractive. Progress in increasing the beam peak current and its brightness, and reducing energy and intensity fluctuations, will allow to produce FELs with larger gain and more reproducible characteristics, making them more useful research tools. The work being carried out on electron sources to reduce the beam emittance while keeping the high peak current and small energy spread is very promising and can lead in the near future to the possibility of pushing the FEL wavelength in the Soft-X-ray region.

References

1. Free Electron Laser Handbook, W. Colson, C. Pellegrini, and A. Renieri eds., North Holland, Amsterdam, in press.
2. C. W. Roberson and P. Sprangle, Phys. Of Fluids B 1, 3 (1989).
3. L. R. Elias and Al., Phys. Rev. Lett. 36, 717 (1976)
4. D.A.G. Deacon et Al., Phys. Rev. Lett., 38, 892 (1977).
5. J. A. Edighoffer et al.,Appl. Phys. Lett. 52, 1569 (1988).
6. S. V. Benson and J. M. J. Madey, Nucl. Instr. and Meth. A32, 55 (1984).
7. S. V. Benson and al., Nucl. Instr. and Meth. A272, 22 (1988).
8. J. E. La Sala, D. A. G. Deacon, and J. M. J. Madey, Phys. Rev. Lett. 59, 2047 (1988).
9. B. E. Newnam et Al., IEEE J. Quantum Elec. QE-21, 867 (1985)
10. D. W. Feldman and Al., IEEE J. Quantum Elec. QE-23, 1476 (1987).
11. K.E. Robinson et al., Nucl. Instr. and Meth. A259, 49 (1987).
12. L. Vintro et al., Phys. Rev. Lett. 64, 1662 (1990).
13. R. Bonifacio, C. Pellegrini, and L. Narducci, Opt. Commun. 50, 373 (1984).
14. P. Sprangle and R. A. Smith, Phys. Rev. A21,293 (1980).
15. C. Pellegrini, Nucl. Instr. and Meth., A272, 364 (1988).
16. W. M. Fawley, D. Prosnitz, and E. T. Scharlemann, Phys. Rev. A30, 2472 (1984).
17. W.A. Barletta and A. M. Sessler, Radiation from fine intense Self Focused Beams at High energy, LLNL Report UCRL-98767 (1989).
18. C. W. Roberson, IEEE J. Quantum Electr., QE-21, 860 (1985).
19. J.C. Goldstein, B. D. Mc Vey and C. J. Elliott, Nucl. Instr. and Meth. A272, 177 (1988).
20. J. B. Murphy and C. Pellegrini, J. Optic. Soc. Am. B2,259 (1985).
21. Proc. Of the ICFA Workshop on Low Emittance Electron Beams, J. B. Murphy and C. Pellegrini eds., Brookhaven National Laboratory Report BNL-52090 (1987).
22. Chemical Dynamics Research Laboratory Coceptual Design Summary, Lawrence Berkeley Laboratory Report PUB-5266 (1990).
23. R. L. Sheffield, E.R. Gray, and J. S. Fraser, Nucl. Instr. and Meth. A272, 222 (1988).
24. S. V. Benson and al., Nucl. Instr. and Methods A250, 39 (1986).
25. K. Batchelor and Al., Development of a High Brightness Electron Gun for the Accelerator Test Facility at Brookhaven, Proc. European Particle Accelerator Conf., p. 954, Rome 1988.
26. R.L. Sheffield et al., RF Photoelectron Gun Experimental Performance, Proc. Linac Conf., CEBAF Rep. 89-001, p. 520 (1989).
27. K.J. Kim and Y.J. Chen, RF and Space-Charge Induced Emittances in Laser-Driven RF Guns, Proc. Linac Conf., CEBAF Rep. 89-001, p. 322 (1989).
28. J. G. Gallardo and R.B. Palmer, Preliminary Study of Gun Emittance Correction, Brookhaven National Laboratory Report BNL-43862 (1990).
29. See for instance P. B. Wilson and J. E. Griffin, High Energy Electron Linacs; Application to Storage ring RF System and Linear Colliders, in Physics of High Energy Particle Accelerators, R.A. Carrigan et al. eds., AIP Confg. Proc. 87, p. 450 (1982).
30. V.E. Balakin et al., VLEPP: Transverse Beam Dynamics, Proc. 12th Int. Conf. on High Energy Accelerators, Fermilab, p. 119 (1984).