The SLAC soft X-ray high power FEL


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We discuss the design and performance of a 2 to 4 nm FEL operating in Self-Amplified Spontaneous Emission (SASE), using a photoinjector to produce the electron beam, and the SLAC linac to accelerate it to an energy of about 7 GeV. Longitudinal bunch compression is used to increase the peak current to 2.5 kA, while reducing the bunch length to about 40 μm. The FEL field gain length is about 6 m, and the saturation length is about 60 m. The saturated output power is about 10 GW, corresponding to about $10^{14}$ photons in a single pulse in a bandwidth of about 0.1%, with a pulse duration of 0.16 ps. Length compression, emittance control, phase stability, FEL design criteria, and parameter tolerances are discussed.

1. Introduction

Free electron lasers (FELs) have until now been limited to the infrared, visible and near UV part of the electromagnetic spectrum. Recent progress in FEL physics and technology is changing this situation, and an effort is now under way to design and build FELs operating at wavelengths shorter than 100 nm. Three main avenues are being followed to reach this goal: FELs oscillators based on storage rings; FEL oscillators based on linacs; harmonic generation; linac-based FELs operating in the Self Amplified Spontaneous Emission (SASE) mode.

The last approach has been followed by a SLAC-UCLA-LBL-LLNL collaboration [1] to design a 2 to 4 nm soft X-ray FEL utilizing the existing SLAC linac and the possibility it offers to produce high brightness electron beams of energy up to 50 GeV. The main characteristics of this soft X-ray FEL are given in Tables 1 and 2.

A SASE FEL avoids the use of optical cavities by operating as a single pass, high gain amplifier starting from spontaneous radiation [2,3]. In the soft X-ray region mirrors are lossy and subject to damage from the radiation. Hence avoiding optical cavities offers a definite advantage.

The soft X-ray FEL offers the possibility of producing 2 to 4 nm radiation with peak power of about 10 GW, in a subpicosecond pulse, as shown in Table 2. Such characteristics are very desirable for applications, such as single shot X-ray imaging of biological samples.

The SASE FEL can be seen as an extension of present synchrotron radiation sources, enhancing their average and peak brightness in the nanometer wavelength region by many orders of magnitude, as shown in Table 3. Atomic lasers have also been operated in SASE down to 4.5 nm, with an energy per pulse of 10 μJ, and peak power of 50 kW [4]. When compared to

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Table 1
Soft X-ray FEL: electron beam and undulator characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>7</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>2500</td>
</tr>
<tr>
<td>Normalized emittance, rms (mm mrad)</td>
<td>3</td>
</tr>
<tr>
<td>Uncorrelated energy spread, rms</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Undulator period (cm)</td>
<td>8.3</td>
</tr>
<tr>
<td>Undulator magnetic field (T)</td>
<td>0.78</td>
</tr>
<tr>
<td>Undulator parameter</td>
<td>6</td>
</tr>
<tr>
<td>Betatron wavelength (m)</td>
<td>30</td>
</tr>
<tr>
<td>Undulator length (m)</td>
<td>60</td>
</tr>
</tbody>
</table>
these atomic lasers the soft X-ray FEL has the advantage of tunability, larger peak power, and much shorter pulse duration.

The SASE approach requires electron beam with very large six dimensional phase space density to obtain a large gain and limit the undulator length needed to reach saturation. It also requires additional focusing in the undulator to increase the electron beam density and thus increase the gain [5].

Until very recently it was impossible to produce electron beams with the properties needed for a SASE FEL at short wavelength. Two recent developments have changed this situation, and opened the possibility to build a linac based soft X-ray FEL. The first is the development, at Los Alamos and elsewhere, of RF photocathode electron guns capable of delivering low emittance (about 3 mm mrad, normalized, rms), high charge (1 nC or more), electron beams [6]. The second is the development at SLAC, as part of the SLC project and the work on linear colliders, of the tools and understanding necessary for the transport, acceleration, and compression of electron bunches without dilution of the phase space density [7].

Following the work of ref. [1], showing the feasibility of a soft X-ray FEL, we have continued a more detailed study of this system, to understand its limitations and optimize the design. In particular we have studied the sensitivity of the system to changes in the beam parameters due to fluctuations occurring in the electron source, the linac, and the compressors, and to errors in the undulator magnetic field and in the focusing system.

In this paper we report the results of these studies, and discuss some modifications of the initial design that have been introduced to make the operation less sensitive to fluctuations.

2. Performance characteristics and error tolerances

The main components of the SLAC soft X-ray FEL, as described before [1], are: (1) a high brightness, RF photocathode electron gun; (2) a 7 GeV section of the SLAC linac; (3) beam transport and compressor systems; (4) beam diagnostics and controls; (5) a 60 m long undulator, including additional focusing; and (6) photon beam lines and experimental stations.

To study the system tolerance to errors and fluctuations we use as a figure of merit the FEL field gain length $L_o$, describing the exponential growth of the field amplitude, $A(z)$, along the undulator axis, $z$,

$$A(z) = A_0 e^{z/L_o}.$$  

(1)

The field gain length defines the undulator length, $L_{sat}$, needed to reach saturation (approximately $L_{sat} \approx 10L_u$). In a one dimensional theory $L_G = \lambda_u/4\pi$, where $\lambda_u$ is the undulator period, and $\rho$ is the FEL parameter [2]. The FEL parameter is defined as

$$\rho = \left( \frac{K \Omega_p}{4 \pi c/\lambda_u} \right)^{2/3},$$

where $K$ is the undulator parameter, $\Omega_p$ is the relativistic beam plasma frequency [2], and $\gamma = E/mc^2$ with $E$ the electron energy. The power at saturation is approximately given by $P_{sat} \approx \rho I_p E$, where $I_p$ is the beam peak current.

Notice that the FEL design parameters are chosen so that the following conditions, necessary for high gain operation and for the validity of the one dimensional theory [5], are satisfied: (a) beam emittance, $\epsilon$, smaller than the wavelength: $\epsilon < \lambda/4\pi$; (b) beam energy spread, $\sigma_E$, smaller than the FEL parameter: $\sigma_E < \rho$; (c) undulator length, $L_u$, larger than the gain length: $L_u \sim L_{sat} \gg L_G$.

As we will see, satisfying conditions (a) and (b) with sufficient margin results in an FEL which is not too sensitive to variations in the beam parameters.

2.1. Focusing

The SLAC soft X-ray FEL uses a planar undulator approximately 60 m in length. The natural betatron wavelength of the undulator is 350 m, and focusing is provided only in one plane. Additional focusing - larger than what the undulator itself provides - is
required to increase the electron density and the FEL gain. An optimum value of the focusing is expected to correspond to a betatron wavelength of the order of 2π times the field gain length [5], in our case about 30 m. The simulations give an optimum value very near to this.

The undulator is a pure permanent structure to which an external quadrupole system, using a FODO lattice, has been added. Using a pure permanent magnet undulator, the field generated by the quadrupoles and the undulator field add linearly within tight tolerances [8].

We have considered several FODO lattices with different quadrupole and drift space lengths, and different magnetic field gradients. One example considered in ref. [8], has a quadrupole aperture radius of 6 cm, quadrupole and drift space length of 40 cm, and can produce a 30 m betatron wavelength with a field gradient of 15 T/m. We have studied other solutions, changing the quadrupole length and the field gradient. The result is that with a FODO lattice with moderate field gradient and a phase advance per cell of 10° to 15° we can produce the desired betatron wavelength of 60 to 30 m.

In the absence of additional focusing, using only the natural undulator focusing the field gain length is too large to be acceptable. The field gain length is reduced to 7.2 m for a betatron wavelength of 60 m, to 5.6 m for a betatron wavelength of 30 m, and reaches a minimum of 5 m at a betatron wavelength of about 20 m. For stronger focusing, and betatron wavelength shorter than about 20 m, the gain length grows again, as expected [9].

Alternative methods of providing the focusing are also being investigated, either by shaping the pole profile [10], or by adding permanent magnets in a quadrupole configuration to a flat pole permanent magnet undulator structure [11].

2.2. Beam parameter studies

The normalized beam emittance and peak current assumed in the design have already been demonstrated [6,7]. It is however important to determine what is the effect of changes in the beam emittance, current, and energy spread on the FEL power.

We have performed extensive numerical studies of the FEL using the codes FRE3D and TDA3D [9]. These codes have been modified to include the effect of additional quadrupole focusing.

We have considered changes in the beam emittance, peak current, and energy spread. A change in the normalized, rms emittance from the nominal 3 mm mrad to 4 mm mrad changes the field gain length from 5.6 m to 6.4 m. A change in beam peak current from 2500 to 2000 A changes the field gain length from 5.6 m to 6.4 m. A change in the uncorrelated energy spread from $4 \times 10^{-4}$ to $6 \times 10^{-4}$ increases the field gain length from 5.6 m to 6.4 m.

These results show that the sensitivity of the FEL performance to changes in beam parameters is not strong, and that limited changes, of the order of 25–50%, in the beam emittance, current, and energy spread produced by the source–linac system can be tolerated. In the case of a simultaneous beam current reduction to 2000 A, emittance increase to 4 mm mrad, and energy spread increase to $5 \times 10^{-4}$, the field gain length is increased to 7.6 m. To reach saturation in this worst case we need an undulator length of 75 m, compared to 60 m for the reference case of Table 1. We can make the FEL less sensitive to beam parameters changes by choosing an undulator length corresponding to this worst case. Notice also that the change in output power when the undulator is longer than the saturation length is small, so that a choice of a longer undulator does not affect the FEL negatively.

2.3. Undulator tolerances

Simulations including the effects of undulator and quadrupole field random errors have been performed using the code FRE3D [9], and for a fixed undulator length of 60 m. The code includes also the possibility of correcting the trajectory perturbations due to field errors by introducing in the simulation a system of beam position monitors and steering magnets.

The results of these calculations show that, for a fixed undulator length, the output power decreases rapidly if the beam misalignment, or the undulator errors, are increased. An rms beam steering error of 30 μm reduces the output power to one third of the ideal case. Similarly an rms undulator error of 0.2% reduces the output power to one third of the ideal case.

The 30 μm alignment error can be compared with the beam radius in the undulator of about 50 μm. To avoid a large reduction in output power we must control the beam alignment to about half the beam size. A 0.2% undulator error, and a 30 μm alignment error, are within the present state of the art [7,8]. Assuming that the we satisfy these tolerances and using the beam parameters of Table 1, we obtain the FEL characteristics given in Table 2.

3. Electron transport, acceleration and compression

The FEL design starts with a bunch generated by the RF photocathode gun with an energy of 10 MeV, a charge of 1 nC, all rms length of 0.5 mm, a normalized rms emittance of 3 mm mrad, and an energy spread of 0.2%. This bunch is accelerated to 7 GeV and compressed longitudinally by a factor of ten to reach a
peak current $I = 2.5$ kA, while preserving the emittance and keeping the peak to peak energy spread below 0.2%, $\Delta E/E < 0.2%$.

Three issues are important in designing the compression system [12]: (1) the longitudinal wakefield in the linac, which increases the beam energy spread, and is larger for short bunches; (2) the transverse wakefield and RF deflection in the linac, which increase the beam emittance; the transverse wakefield is more severe for long bunches; and (3) the effect of phase and charge jitter, which changes the bunch length and therefore the peak current in the beam.

The transverse wakefield depends on the alignment errors in the SLAC linac. The emittance dilution effects due to transverse wakefields, RF deflections, and dispersive effects have been modeled in the SLAC linac assuming 150 $\mu$m random misalignments of the quadrupole and beam position monitors, 300 $\mu$m rms random misalignments of the accelerating structures, and a transverse-longitudinal coupling of $2 \times 10^{-4}$ for the RF deflection [13]. The transverse beam position jitter has been assumed to be equal to the rms beam size.

To find a compromise between a reduction of the longitudinal wakefield and of the transverse wakefield the bunch compression is done in two stages, reducing initially the bunch length to about 0.2 mm at 100 MeV, and then to about 0.04 mm at 2 GeV, followed by acceleration to the final energy of 7 GeV. With this configuration the emittance blow-up is smaller than 25%.

The evolution of longitudinal phase space with this compression scheme has been evaluated including the effects of longitudinal wakefields, curvature of the RF wave, and phase and intensity jitter. In the SLAC soft X-ray FEL the longitudinal emittance from the electron source is extremely small. When we execute a 90° rotation in longitudinal phase space to compress the bunch, the result is very sensitive to time jitters between the laser and the RF system. A small change in the input bunch phase can result in large changes in the final bunch length, and hence in the output current.

To reduce the sensitivity to phase jitter the beam is overcompressed in the second compressor beyond the 25–30 $\mu$m minimum, by rotating in phase space by more than 90°. This slight over-compression and subsequent acceleration from 2 to 7 GeV tends to cancel upstream errors, thus relaxing the timing and intensity jitter requirements. After the first compression the longitudinal beam distribution is still nearly Gaussian. After the second compression the beam distribution is more sharply peaked and has long tails, as shown in Fig. 1. Note that between the horns of the bunch, the peak current is everywhere larger than 5 kA and that the full width of the energy distribution is 0.04%, a larger current and a smaller energy spread than what is required. If we use energy collimation to remove the energy tails, the peak current at the center of the bunch is about 3 kA.

Defining the jitter tolerance as the amount of change in a parameter that changes the full width of the bunch distribution by 10%, we find in this system of bunch compression [12] that the tolerance to phase jitter is $\pm 0.45^\circ$, corresponding to about $\pm 0.5$ ps time jitter, and that the gun current variation tolerance is $\pm 2.2%$. These tolerances can be met using available equipment.

4. Noise and fluctuations

Since the FEL starts from noise, the line width and time structure of the radiation pulse are determined by the evolution of the system, and we can also expect large shot to shot fluctuations in the output power level. This problem has been studied recently [14], showing that the most important parameter determining the characteristics of the output radiation is the number of cooperation lengths $L_c$, defined as $L_c = \lambda/4\pi\rho$, within the bunch length. In our case this number is very large, of the order of 400. This is a favorable conditions, leading to small fluctuation in the output power level, and in the saturation length. For our FEL the fluctuation level in output power is smaller than 10%. The line width is of the order of the FEL parameter $\rho$, i.e. $\sim 0.15%$. The line width for the soft X-ray FEL has also been calculated numerically using a 3-D code including slippage effects and starting from VI. NEW CONCEPTS
noise [15]. The results agree with a line width given by ρ.

5. Conclusions

All the simulations done for the SLAC soft X-ray FEL show that the design parameters chosen are stable with respect to fluctuations in beam emittance, energy spread, and peak current. The required tolerances on the fluctuations of these quantities are within the present state of the art of accelerator technology and bunch compression.

The requirement on undulator tolerances, and beam transport through the undulator are also obtainable using existing technology.

The conclusion is that a soft X-ray FEL, producing unprecedented radiation brightness, is now within reach. Such a system will provide dramatic improvements over synchrotron radiation sources, and will open new scientific possibilities.

References

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