SOFT X-RAY FREE-ELECTRON LASER WITH A 10-TIME REDUCED SIZE

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Abstract

We propose an ultra-compact soft X-ray superradiant FEL at 30 nm driven by a 150 MeV beam. The total length of such a FEL is less than 30 m, which is 10 times shorter than the length of a typical soft X-ray FEL. The key concept is to laser modulate the electron emission at the photoinjector and then compress the electron macro-bunch by linac and chicane magnet to achieve a soft X-ray bunching frequency in front of an FEL undulator. With an initial 10-ppm bunching factor, we calculated a sub-GW radiation power at 32.2 nm from a 3m long undulator.

INTRODUCTION

A free-electron laser (FEL) is commonly perceived by people with a large size and high cost. The most notable soft X-ray FEL, FLASH, has been commissioned since 2005, producing GW level soft X-ray laser from a 260-m long facility [1]. Following FLASH's success, the Linac Coherent Light Source (LCLS) also demonstrated high brightness hard-X-ray laser radiation in 2009 from a mile long faciltiy [2]. More recently the RIKEN of Japan announced X-ray lasing at 0.08 nm from its kilometer long FEL facility, SACLA [3]. This sequence of successful demonstrations of X-ray FELs calls for the need to make such a powerful light source available for majority user groups. To benefit a larger group of X-ray users, seveal proposals have been brought up to reduce the cost and size of an X-ray FEL. In particular, the proposed X-ray FEL driven by a laser wake field accelerator has been a promising approach [3]. We study in this paper a 10-time size reduced soft X-ray FEL based on the well developed, much more reliable conventional RF accelerator technology.

Figure 1 shows the system layout of the proposed soft X-ray FEL. We propose to modulate the emission of the photocurrent from the injector at a few hundreds of THz by using a laser. Following the photoinjector, the linacs compress the electron beam through velocity bunching to increase the electron bunching frequency by about 10 times. Finally the chicane magnet further compresses the whole electron bunch by 3 times to reach an electron bunching frequency close to the soft-X-ray frequency. The pre-bunched electron beam, permitting fast buildup of the FEL power, greatly reduces the need for a long FEL undulator. The proposed solenoid-derived staggered-array micro-undulator also greatly reduces the need of a long high energy electron accelerator. We delineate in the following the design for each major component in the beam line.

ELECTRON INJECTOR

The use of a THz-pulse-train laser to generate a THz-pulse-train electrons from a photoinjector has been proposed and implemented [4,5]. Since the electron relaxation time in a copper is about 10^{-19} sec., it could be possible to induce the emission of an electron pulse with a temporal length comparable to 10^{-19} sec. We propose to combine the 3rd and 4th harmonics of an Nd laser at 355 and 266 nm, respectively, into a driver laser pulse for an S-band photoinjector. The driver laser illuminates the copper photocathode, on which the electron emission follows the beating amplitude of the laser at 282 THz. The electron gun accelerates the 282-THz bunched electrons to 5 MeV. As usual, the solenoid following the electron gun is used to compensate emittance growth. An array of linear accelerators continues to boost up the electron energy to 150 MeV.

BUNCHING FREQUENCY MULTIPLICATION

If the target soft X-ray wavelength is 30 nm, the 282 THz bunching frequency in the 5 MeV beam has to be multiplied by 33 times. This can be done by compressing the overall electron pulse by the same factor.

A chicane magnet is popular device to compress an electron bunch. [2] To reduce the length of the overall beam line, we choose to perform the primary bunch compression through velocity bunching [6] in a 2-m long linac immediately following the photoinjector. By using PARMELA, we conducted a computer simulation from the photocathode of the injector to the end of the 2 m long linac. Figure 2 shows the electron pulse length versus the propagation length. The zero position in the plot coincides with the photocathode. The linac starts at 150 cm and ends at 350 cm. At the cathode, the input rms pulse width is 4.25 ps (10 ps FWHM), the total charge is 1 nC, and the initial rms beam radius is 0.75 mm. At the output of the linac, we obtained an rms electron pulse width of 417 fs, average electron energy of 9.86 MeV, rms emittance of 14 mm-mrad, and energy spread of 2.9%. The percentage energy spread can be controlled within 0.2% after the beam is further accelerated to 150 MeV. To achieve the large compression ratio, we accelerate the electron pulse at –8 deg. RF phase, which reduces the average acceleration gradient and

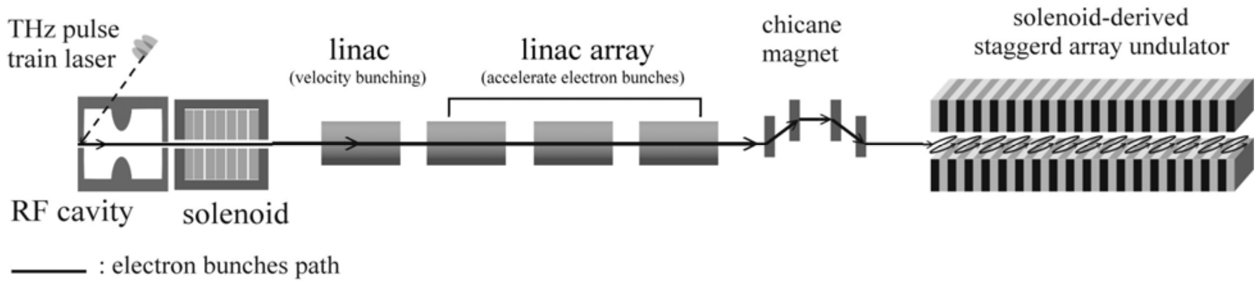

Figure 1: Schematic of superradiant soft X-ray FEL.

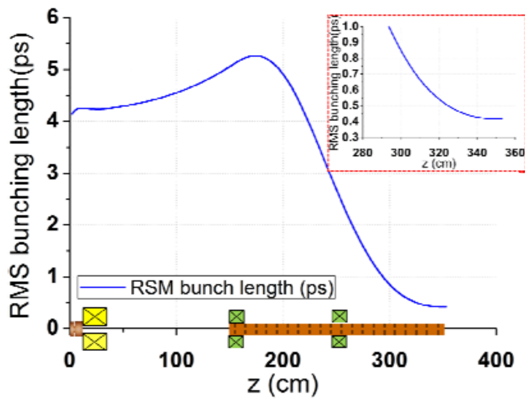

Figure 2: The RMS bunch length versus beam propagation length from photocathode (z = 0) to the end of the first-section linac (z = 3.5 m). At z = 3.5m, the bunch length is compressed to be 1/10 of the initial bunch length at z = 0.

deteriorates the beam emittance during the slow acceleration process. Further optimization is needed to reduce the beam emittance.

At the output of the first linac, the electron beam is continuously accelerated to 150 MeV by an array of 4 S-band linacs, each having a length of 3 m. Once the electron energy reaches 150 MeV, the high energy beam is compressed by a chicane compressor by 3.3 times. The chicane compression is straightforward, as it has been demonstrated in several places [1,2]. Based on the LCLS chicane design, we estimate that the length of the chicane should be less than 6 m.

SOLENOID-DERIVED STAGGERED ARRAY UNDULATOR

After being compressed, the electron bunch has a bunching frequency of 9.3 PHz or a bunch length of 30 nm. If an undulator is properly designed, the pre-bunched electrons can quickly radiate in the undulator with a soft X-ray wavelength at 30 nm or its harmonics. To ease the fabrication of a short-period undulator, we choose the solenoid-derived staggered undulator [8,9]. As Fig. 3 shows, the solenoid-derived undulator is composed of two iron arrays in a solenoid. The iron arrays are displaced in the longitudinal direction by half of an undulator period with respect to each other. The solenoid field is deflected by the iron poles to the transverse direction to form the alternating transverse undulator field. The longitudinal field is advantageous in confining a low energy electron beam. It is also known that the type of undulator has a large tolerance on machining errors of the iron blocks [8,9]. This property is important for the fabrication of a short period undulator.

In our design, the electron beam enters a 3m long solenoid-derived staggered array undulator with an undulator period λ_u= 5mm and gap 0.84 mm. With a saturation field of 2 T in the iron pole pieces, the estimated undulator parameter is a_u = 0.4 [8,9]. From the FEL synchronism condition, the radiation wavelength from the 150 MeV electrons is 32.2 nm. The small undulator gap sets an upper limit of a normalized emittance of 15 mm-mrad to transmit the electron beam.

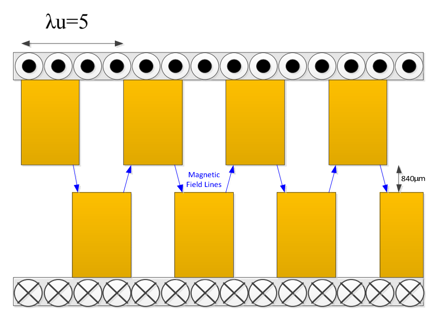

Figure 3: The schematic of a solenoid-derived staggered array undulator. In our design, the undulator period λ_u is 5 mm and gap is 0.84 mm, which give an undulator parameter of 0.4 with a saturation field of 2 T in the iron poles.

SOFT X-RAY FEL

Since the electrons are pre-bunched at the radiation frequency, the electrons produce electron superradiance or coherent synchrotron radiation as soon as they enter the undulator. Without considering the space charge force, beam emittance, energy spread, and power saturation, the radiation power from the coherent synchrotron radiation can be calculated from [12]

$$P = B^2 \left[\frac{\sqrt{\pi}}{2} N_u^2 I^2 \eta \frac{a_u^2}{(1+a_u^2)^2} \right], \quad (1)$$

where B is the bunching factor, N_u is the number of undulator period, I is the electron current, and η = 377 Ω is the intrinsic wave impedance in vacuum. For a 3-m long undulator with undulator period of 0.5 cm, the total number of undulator periods is 600. The peak current of our FEL is 3.3 kA and the beam power is about 495 GW.

With a typical saturation efficiency of 10^{-3} for short-wavelength FEL, the saturation power of our FEL is around 0.5 GW. Therefore, the required bunching factor to reach the saturation power in a 3-m undulator is B = 0.18%. This calculation does not consider beam emittance and energy, and perhaps most importantly the feedback from the radiation field on the electrons. In practice, the bunching factor varies as the electrons radiate and propagate down the undulator. In the following, we adopt the simulation code GENESIS [11] to derive the minimum bunching factor that is required to obtain a sub-GW radiation power from the 3-m long undulator. Table 1 summarizes our design parameters for the electron beam used in the GENESIS simulation.

Table 1: Beam Parameters for Simulating the Soft X-Ray FEL in Genesis

Beam parameters	
Energy	150MeV
Transverse Emittance	2 mm-mrad
Beam Size	80μm
Beam Current	3.3 kA
Energy Spread	0.03%
Bunching Factor	10 ppm

Figure 4 shows the FEL output power versus the undulator length with 10-ppm (blue line) and zero (red line) initial bunching factors. It is seen from the plot that with merely a 10-ppm bunching factor the FEL power builds up to 0.2 GW from the 3-m long undulator, whereas without any prebunching the FEL power is in the noise level. This result can be understood from Fig. 4b, in which, with 10-ppm prebunching, the bunching factor manages to increase due to the radiation feedback, but, with no prebunching, the bunching factor can not grow from the negligible radiation feedback. In our simulation, even though we increased the undulator length to 30 m, we still did not observe the exponential growth of the FEL power for the case without prebunching. We should point out that the emittance used in our simulation is smaller than that obtained from the lattice design. However, if we can not further optimize the velocity bunching to reduce the emittance, we could in principle adopt the chicane compression scheme [1] to achieve both the required pulse compression and beam emittance at the cost of a slightly longer lattice length.

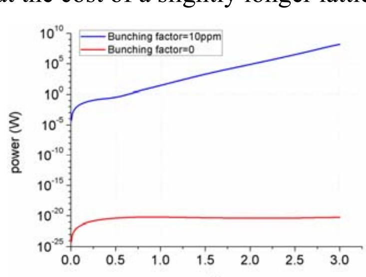

Figure 4: FEL output power versus the propagation length z with 10-ppm (blue line) and zero (red line) initial bunching factors. The undulator starts at z=0 cm, and ends at z=300 cm.

CONCLUSION

We have proposed a 30-m long soft X-ray FEL consisting of a 5MeV photoinjector, few linacs, a magnetic chicane compressor, and a 3m long undulator. We propose to employ both the 3rd and the 4th harmoincs of an Nd laser at 355 and 266 nm, respectively, to illuminate the cathode of the photoinjector. Owing to the beating of the two lasers, the emitted electron beam could be modulated at 282THz. The electrons are further accelerated to 150 MeV and compressed by 33 times during acceleration and in a magnetic chicane. The temporal compression of the electron macropulse increases the electron bunching frequency to 9.3 PHz, corresponding to a soft X-ray wavelength of 32.2nm. We adopt a solenoid-derived staggered array undulator with a 3 m length, 5 mm undulator period, and 840 μm gap. With a solenoid field of 10 kG, we estimate an undulator parameter of 0.4 and a corresponding radiation wavelength of 32.2 nm for a 150 MeV driving beam. With 3.3 kA peak current, 0.03% energy spread, 2 mm-mrad emittance, and 80micron beam radius at the undulator entrance, the GENESIS code predicts 0.2 GW radiation power from the 3m long undulator for an initial bunching factor of merely 10 ppm.

ACKNOWLEDGMENTS

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