A Compact Soft X-ray Free Electron Laser

We propose an ultra-compact soft X-ray superradiant free-electron laser at 30 nm driven by a 150-MeV beam. Its total length is approximately 30 m, which is 10 times shorter than that of an ordinary free-electron laser. The key concept is to laser modulate the electron emission at a photoinjector and then compress the electron macro-bunch by a linac and chicane magnet to achieve a soft X-ray bunching frequency in front of a free-electron laser undulator. We calculated a sub-GW radiation power at 32.2 nm from a ~3 m long undulator for a 150 MeV beam with a 0.1% bunching factor, 0.15% energy spread, 4 mm-mrad emittance, and 10- kA current.

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A free-electron laser (FEL) is commonly perceived 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] 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, a linac compresses the electron beam through velocity bunching to increase the electron bunching frequency by about 12 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 build-up of the FEL power, greatly reduces the need for a long FEL undulator. The proposed solenoid-derived staggered-array micro-undulator, having the advantage of beam confinement by a solenoid field, 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. 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 space-charge induced emittance growth. An array of linacs continues to boost up the electron energy to 150 MeV. 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.

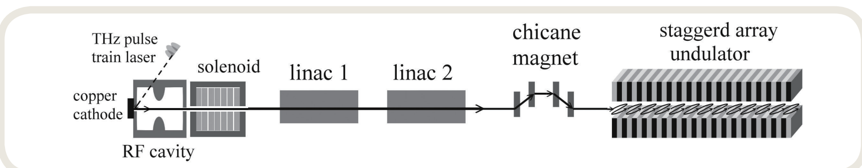

Fig. 1: Schematic of the proposed compact superradiant soft X-ray FEL.

A chicane magnet is a popular device to compress an electron bunch. To reduce the length of the overall beam line, we choose to perform primary bunch compression through velocity bunching[2] in a 3-m long linac immediately following the photoinjector. By using the computer code PARMELA, we conducted a simulation from the photocathode of the injector to the end of the 3-m long linac. To confine the beam and limit the emittance growth, three 30-cm long solenoid coils are mounted on the linac at z = 150, 250, 350 cm with a peak field of 0.8 kG in each coil. Figure 2 shows the variation of the electron pulse length versus distance. The zero position in the plot coincides with the photocathode. The linac starts at 150 cm and ends at 450 cm. At the cathode, the input rms pulse width is 1.12 ps (3 ps FWHM), the total charge is 300 pC, and the initial rms beam radius is 0.5 mm. At the output of the first linac, we obtained an rms electron pulse width of 91 fs, average electron energy of 59 MeV, rms emittance of 4 mm-mrad, and energy spread of 2%. After the beam is further accelerated to 150 MeV, our simulation shows an energy spread approaching 0.15% for the high energy beam. To achieve the large compression ratio, we accelerate the electron pulse at 75 deg. of the RF phase, which somewhat reduces the average acceleration gradient and deteriorates the beam emittance during the slow acceleration process. However, this beam degradation does not prevent us from reaching the final design goal.

The electron beam is continuously accelerated to 150 MeV by a 3-m long S-band linac following the first linac. Once the electron energy reaches 150 MeV, the high-energy electron pulse is compressed in time by a chicane compressor by 3 times. The peak current (bunch charge divided by rms bunch length) of the further compressed beam will reach 10 kA. The chicane compression is straightforward, as it has been demonstrated in several places.[1, 3] Based on the LCLS chicane design, we estimate that the length of the chicane should be less than 6 m. After further compressed in the chicane magnet, the electron bunch has a bunching frequency of 9.3 PHz or a micro-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 so-called solenoid-derived staggered undulator.[4] 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 this type of undulator has a large tolerance on machining errors of the iron blocks. This property benefits to the fabrication of a short period undulator.

In our design, the electron beam enters a 3-m long solenoid-derived staggered array undulator with an undulator period λ_u = 5 mm and gap 0.84 mm. With a saturation field of 2 T in the iron pole pieces, the estimated undulator parameter is 0.4. We adopt the simulation code GENESIS[5] to derive the minimum bunching factor that is required to obtain a sub-GW radiation power from the 3-m long undulator. Figure 3 shows the FEL output power versus undulator length along z. In the simulation, the input parameters are: normalized emittance = 4 mm-mrad, energy spread = 0.15%, peak current = 10 kA, and electron beam radius = 0.08 mm. The blue line and red line represent the output power with initial bunching factors of 1,000 ppm (blue line) and 0.1 ppm (red line), respectively. It is seen from the plot that with merely a 0.1% bunching factor, the FEL power builds up to about 0.3 GW from a 2.8-m long undulator.

References

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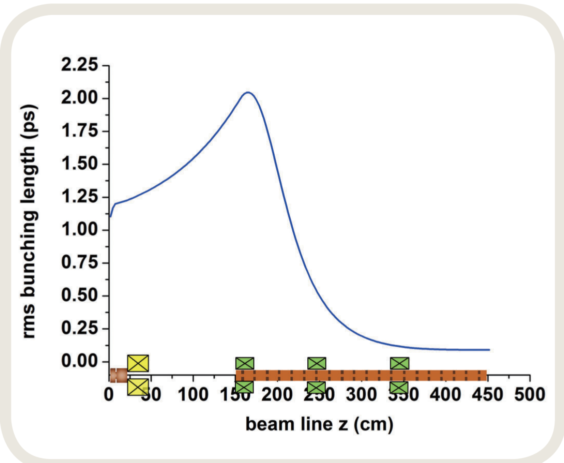

Fig. 2: The rms bunch length versus distance from the photocathode (z = 0) to the end of the first-section linac (z = 4.5 m). At z = 4.5 m, the bunch length is compressed to 1/12 of the initial bunch length at z = 0.

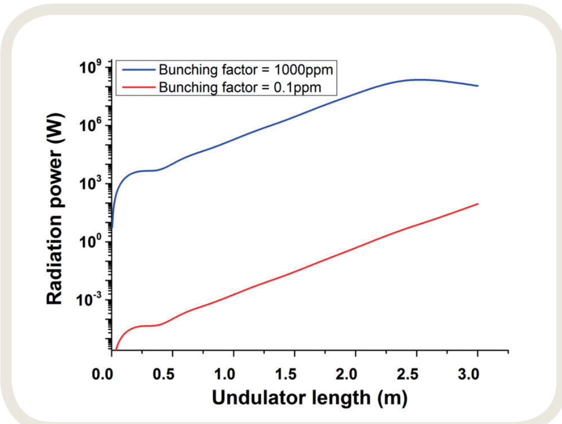

Fig. 3: FEL output power versus the undulator length with 1,000 (blue line) and 0.1 ppm (red line) initial bunching factors. The undulator starts at z = 0 and ends at z = 3 m. The output power reaches 0.3 GW at z = 2.8 m.