GENERATION OF ATTO-SECOND WATER WINDOW COHERENT X-RAY RADIATION THROUGH MODULATION COMPRESSION*

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Abstract

In this paper, we propose a scheme to generate atto-second tunable water window (~2-4 nm) coherent X-ray radiation for future light source applications. This scheme improves the previously proposed modulation compression method [1] by using a low charge, short bunch electron beam at 2 GeV energy, a 200 nm seeding laser, an X-band linac, two opposite sign bunch compressors, and a long wavelength laser to generate a prebunched, kilo-Ampere current beam with a modulation wavelength within the water window. Such a beam sent into an undulator generates a short pulse transverse and temporal coherent soft X-ray radiation. The requirement of initial seeding laser power is low.

INTRODUCTION

Ultra-short water window (2-4 nm) soft X-ray sources have important applications in biology, chemistry, condense matter physics, and material science. In recent years, there are growing interests in generating single atto-second x-ray radiation using Free Electron Lasers (FELs) [2, 3, 4, 5, 6, 7, 8, 9]. In our previous study, a modulation compression scheme was proposed to compress the initial laser modulation to generate short wavelength X-ray radiation [1]. The scheme consists of a modulator, a chirper, a bunch compressor, a unchirper, and a opposite sign bunch compressor. For a beam after initial laser modulation, its longitudinal distribution function can be written as:

$$f(z,\delta) \quad = \quad F(z, \frac{\delta - A\sin(kz)}{\sigma}) \qquad (1)$$

where $A = V/E$ is the initial laser modulation amplitude, $\delta = \Delta E/E$, and k is the modulation wave number. After the final compression, the beam longitudinal distribution function will be

$$f(z,\delta) \quad = \quad F(Cz, \frac{\delta - CA\sin(kCz)}{C\sigma}) \qquad (2)$$

where $C = 1/(1 + R_{56}h)$ is the compression factor of the first bunch compressor. The longitudinal modulation wavelength is reduced by a factor of C and modulation amplitude is increased by a factor of C. In the previous study, in order to effectively chirp and to unchirp the modulated electron beam, two lasers were used as chirpers before the two bunch compressors. The fluctuation of laser field amplitude will cause the fluctuation of electron beam chirp. For a large compression factor, e.g.100, a small change of electron beam chirp will cause a large change of compression factor and hence the compressed modulation wavelength. In this study, we propose using only one laser to unchirp the electron beam after the first bunch compressor for the generation of attosecond water-window soft X-ray radiation. The electron beam chirp before the first bunch compressor is provided by conventional X-band RF linac that could have better phase and amplitude stability than the laser field. This could significantly reduce the requirement of laser field stability for the modulation compression.

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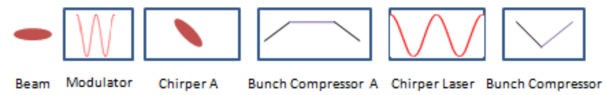

Figure 1: A schematic plot of the accelerator lattice for generation atto-second X-ray radiation through compression.

GENERATION OF ATTO-SECOND BUNCHING THROUGH MODULATION COMPRESSION SCHEME

In this section, we describe the scheme to generate atto-second prebunched current modulation at the water window wavelength using the improved compression scheme. A schematic plot of this scheme is given in Fig. 1. It consists of a 200 nm laser modulator, an X-band linac, a chicane type bunch compressor with positive R_{56}, a 10 µm laser modulator as unchirper, and a dog-leg type bunch compressor with negative R_{56}. A short bunch (100 µm) 10 pC electron beam at 2 GeV energy with an energy spread of 2×10^{-6} passes through a modulator with 200 nm laser wavelength to get initial energy modulation. Figure 2 shows the longitudinal phase space distribution after the beam moves through the modulator. A fraction of the electron beam is energy modulated with a modulation width around 30 fs. The uncorrelated energy spread of the beam is increased by 0.56 keV due to the incoherent synchrotron radiation (ISR) effects inside the undulator using an estimate from Reference [9]. This electron beam will then transport through an X-band linac to obtain a global correlated energy chirp of $-24.698/m$. Here, we have assumed that the X-band linac operates at 90 degree phase, and there is no net energy acceleration. Such a chirp will require a

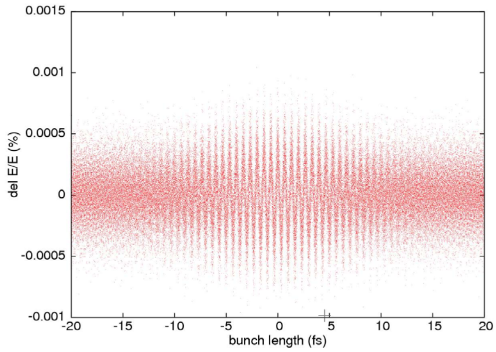

Figure 2: Longitudinal phase space distribution after the initial modulation.

total 207 MV voltage across the X-band linac running at 11.4 GHz. Assuming an average acceleration gradient of 70 MV/m in the X-band linac, this corresponds to a linac of 3 meters long. After the beam goes through the X-band linac, it passes through a standard C shape chicane bunch compressor. Here, we have assumed that the R_{56} of the chicane is about 4 cm with $T_{566} = -\frac{3}{2}R_{56}$ and $U_{5666} = 2R_{56}$. As an electron beam passes through a bending magnet, the incoherent synchrotron radiation causes the increase of the uncorrelated energy spread. We assumed 0.4 keV increase of uncorrelated energy spread based on a chicane design using four 4 meters bending magnets each with 0.0655 radian bending angle. After the beam passes through this bunch compressor, the total bunch length of the beam is compressed to about 1μm due to the large compression factor of 100. This beam is transported through another laser modulator with 10μm resonance wavelength. Since the modulation wavelength is much longer than the bunch length, this modulator works as an unchirper to remove the global energy chirp across the beam. Another 0.5 keV increase of uncorrelated energy spread is added to the beam due to the ISR effects inside the undulator. After the beam transport through the laser modulator, it passes through a dog-leg type bunch compressor that can provide opposite sign R_{56} compared with the first bunch compressor. The requirement of the R_{56} from this bunch compressor is a factor of C smaller than the first bunch compressor. For a compression factor of 100 in the first bunch compressor, the R_{56} for the second bunch compressor is about 0.4 mm. Figure 3 shows the longitudinal phase space of the beam at the end of the second bunch compressor. It is seen that after the second bunch compressor, the initial 30 fs modulated beam is compressed to a width around 300 atto-seconds. The initial uncorrelated energy spread of 2×10^{-6} has risen to about 2×10^{-4}. This energy spread is still small enough for generating coherent X-ray radiation in an undulator downstream. Figure 4 shows the projected current profile for this prebunched beam. Given the initial 30 A current, the prebunched current with 2 nm wavelength modulation reaches more than 4.5 kA. Such a highly prebunched beam can be used to generate coherent atto-second water-window X-ray

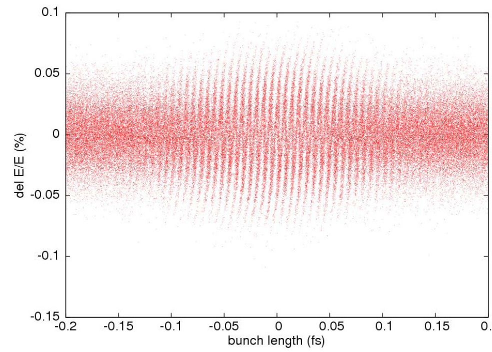

Figure 3: Longitudinal phase space after the compression scheme.

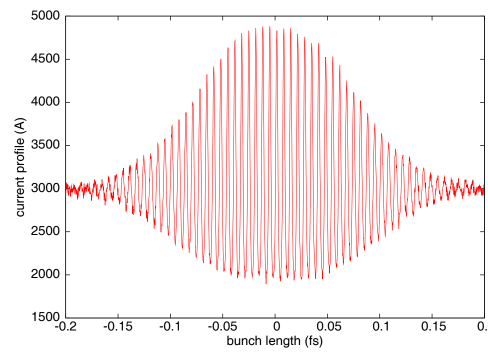

Figure 4: Beam current profile after the compression scheme.

radiation through a short undulator.

Two laser modulators, one for modulation seeding and the other for global correlated energy unchirping, are used in this scheme for atto-second generation. Figure 5 shows the relative energy modulation from the seeding laser and from the unchirping laser. The amplitude of the seeding

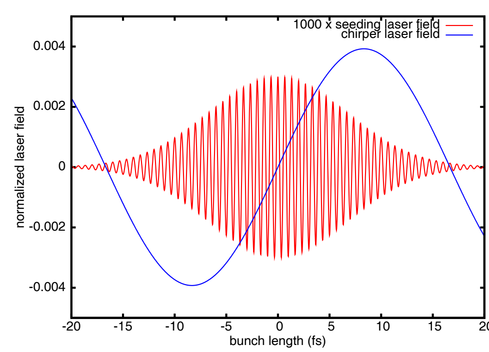

Figure 5: Relative energy modulation from the seeding laser and the unchirping laser.

laser is very small due to the fact of compression amplification. The amplitude of the unchirping laser is relatively large in order to remove the amplified initial energy chirp by the first bunch compressor. Figure 6 shows the laser power needed as a function of undulator magnet field strength in the first modulator. For 1 Tesla undulator magnet field, the required 200 nm laser power is only about 0.7 MW with an undulator length of 35 cm and period of 11 cm. Figure 7 shows the laser power needed as a function

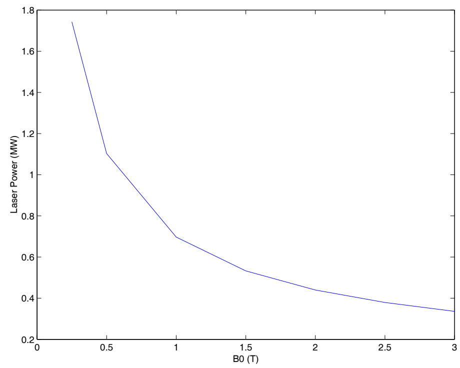

Figure 6: Seeding laser power as a function of undulator magnetic field strength.

of undulator magnet field strength in the second modulator unchirper. Assume 1 Tesla magnetic field, it will require around 11 GW laser power inside a 1 m undulator with a period of about 40 cm. In both modulators, we have as-

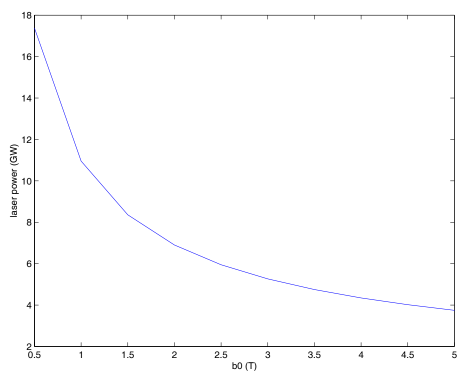

Figure 7: unchirping laser power as a function of undulator magnetic field strength.

sumed the laser waist spot size of 1 mm.

In above example, we have assumed an initial seeding laser modulation width of 30 fs. By using a shorter seeding laser pulse length, one can obtain even shorter atto-second prebunched beam after the factor of 100 compression. Figure 8 shows the current profile after the compression by using an initial a few-cycle carrier wave laser. The final prebunched current has a width of around 33 atto-second and more than 4.5 kA peak current.

ATTO-SECOND SOFT X-RAY RADIATION

As a preliminary study, we used a single slice of above prebunched beam and transported through an undulator to generate X-ray radiation. Figure 9 shows the 2 nm X-ray radiation power evolution through the undulator. It is seen that the radiation reaches a saturation level of 10 GW output power within 5 meters. A further time-dependent FEL

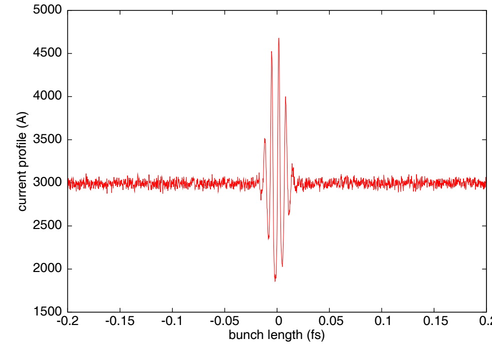

Figure 8: Longitudinal phase space distribution after compression with an initial a few cycle laser seeding.

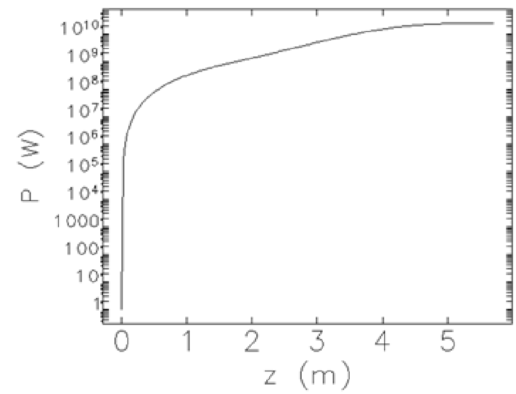

Figure 9: X-ray radiation power evolution through the undulator.

simulations will be done to illustrate the temporal property of the radiation.

DISCUSSIONS

In above scheme, in order to chirp the beam before the first bunch compressor, we need to use a section of the RF X-band linac with a total voltage of 207 MV. This is not be cost effective. It can be improved by using a modified scheme as shown in Fig. 10. In this scheme, a chirped beam is sent into the first laser modulator for initial seeding. By doing the chirping first instead of seeding first, it allows one to use the full linac to generate such a energy chirp. Inserting a chicane with a reasonable compression factor inside such a linac will provide the same amount of chirp needed in this compression scheme but a factor of chicane

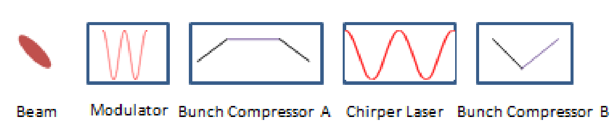

Figure 10: A schematic plot of the modified accelerator lattice for modulation compression.

compression factor less total voltage from the linac. For a chirped beam with increasing energy deviation from the center, the edge electrons might not get the same energy modulation as the unchirped beam. To check this idea, we ran simulation of a section of chirped electron beam passing through a laser and undulator fields. The longitudinal phase space distributions before and after the modulation, and the longitudinal phase space with initial chirped beam (after removing the chirp) and unchirped beam are shown in Fig. 11. It is seen that the two longitudinal phase-space

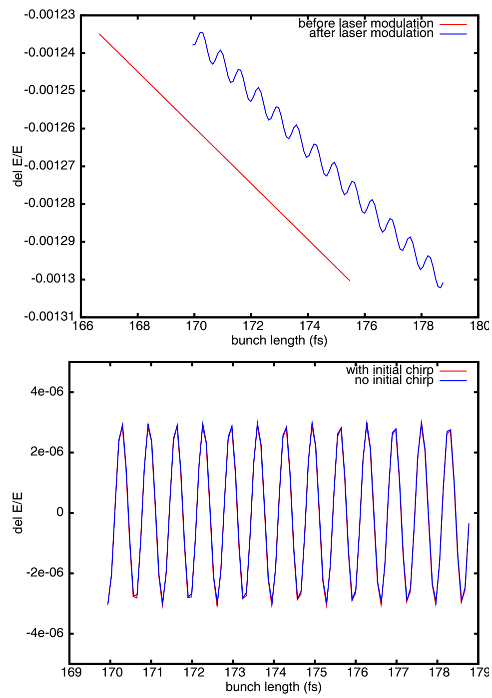

Figure 11: Longitudinal phase space distribution before and after the modulation for an initial chirped beam (top), longitudinal phase space with initial chirped beam (after removing the chirp) and unchirped beam (bottom).

distributions with and without initial energy chirp are close to each other. This suggests that the energy deviation for the chirped electrons does not have significant effects on the initial energy modulation. This is due to the fact that laser electron resonant interaction inside the short undulator has a large bandwidth. Such a bandwidth allows the chirped electrons to get the same energy modulation.

In this paper, we proposed a scheme to generate water-window atto-second coherent X-ray radiation through modulation compression. This scheme allows one to tune the final X-ray radiation wavelength by adjusting the compression factor. It also allows one to control the final radiation pulse length by controlling the seeding laser pulse length. However, there also exists some technical challenges associated with this scheme. These include synchronization between the electron beam and the seeding laser and the unchirping laser, stability of the laser field in the unchirping modulator. Meanwhile, some collective effects such as coherent synchrotron radiation and geometry wakefields inside the undulators might affect the modulation signal inside the beam and need to be further studied.

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