Efficient frequency doubler for the soft X-ray SASE FEL at the TESLA Test Facility

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Abstract

This paper describes an effective frequency doubler scheme for SASE free electron lasers. It consists of an undulator tuned to the first harmonic, a dispersion section, and a tapered undulator tuned to the second harmonic. The first stage is a conventional soft X-ray SASE FEL. Its gain is controlled in such a way that the maximum energy modulation of the electron beam at the exit is about equal to the local energy spread, but still far away from saturation. When the electron bunch passes through the dispersion section this energy modulation leads to effective compression of the particles. Then the bunched electron beam enters the tapered undulator and produces strong radiation in the process of coherent deceleration.

We demonstrate that a frequency doubler scheme can be integrated into the SASE FEL at the TESLA Test Facility at DESY, and will allow to reach 3 nm wavelength with GW-level of output peak power. This would extend the operating range of the FEL into the so-called water window and significantly expand the capabilities of the TTF FEL user facility.
1 Introduction

The soft X-ray FEL at the TESLA Test Facility at DESY (TTF FEL) will cover a spectral range between approximately 60 nm and 6 nm wavelength. The minimum wavelength of 6 nm is determined by the maximum electron beam energy of 1 GeV. It would be extremely interesting to extend this range into the so-called water window, i.e. the range between the K-Absorption edges of carbon and oxygen at 4.38 nm and 2.34 nm, respectively. This would allow time-resolved studies of organic molecules above the carbon K-edge, and, for example, the investigation of thick, hydrated biological samples by X-ray microscopy without the need of shock-freezing [1,2]. There are several techniques under consideration to reach this goal: A X-ray SASE FEL at shorter wavelengths, which requires higher beam energy or a shorter undulator period, and the generation of harmonics through a nonlinear mechanism driven by bunching at the fundamental.

There are basically two methods to up-convert the fundamental radiation frequency via nonlinear harmonics. These methods are the generation of third harmonic radiation in a planar SASE undulator through a nonlinear mechanism driven by bunching at the fundamental frequency, and a two-undulator (second) harmonic generation scheme, also referred to as the "after-burner" method.

SASE FELs are capable to produce powerful radiation not only at the fundamental frequency, but also at higher harmonics. When a beam is strongly bunched in the sinusoidal ponderomotive potential formed by the undulator field and the radiation field of the fundamental frequency, the electron beam density spectrum develops rich harmonic contents. Coherent radiation at the odd harmonics can be generated in a planar undulator and significant power levels for the third harmonic can be reached before the FEL saturates (see [3–6] and references therein). It is expected that the power of the transversely coherent third-harmonic radiation can approach the 1% level of the fundamental power at the TTF. Since the nonlinear harmonic generation occurs naturally in a planar undulator, no additional FEL hardware components are required for this method.

An idea of using two undulators, with the second undulator resonant to one of the harmonics of the first one, was considered in [7–9] (it is also referred to as the "after-burner" method). The first undulator is long enough to reach saturation and produce strong spatial bunching in harmonics. The bunched beam generates coherent radiation in the second undulator which follows immediately the first one. The main problem with this approach is the large induced energy spread which will be generated by the bunching of the electron beam at the fundamental frequency. While this energy spread is necessary for the bunching, it degrades the performance of the radiator section at the harmonic frequency. Another method to generate higher harmonics is the high-gain harmonic generation scheme (see [10,11] and references therein). It should be noted that all previous studies of such frequency multiplication schemes were performed in the framework of the steady-state approach, and the question arises how effectively they work in the case of a SASE FEL.

In this paper we propose an effective frequency doubler scheme for a SASE FEL. It consists of an undulator tuned to the first harmonic, a dispersion section, and a tapered undulator tuned to the second harmonic (see Fig. 1). The first stage is a conventional...
soft X-ray SASE FEL. The gain of the first stage is controlled in such a way that the maximum energy modulation of the electron beam at the FEL exit is about equal to the local energy spread, but still far away from saturation. When the electron bunch passes through the dispersion section this energy modulation leads to effective compression of the particles. Then the bunched electron beam enters a tapered undulator, and from the very beginning produces strong radiation because of the large spatial bunching. The strong radiation field produces a ponderomotive well which is deep enough to trap the particles, since the original beam is relatively cold. The radiation produced by these captured particles increases the depth of the ponderomotive well, and they are effectively decelerated. As a result, much higher power can be achieved than for the case of a uniform undulator. In addition, the output radiation exhibits excellent spectral properties due to the suppression of the sideband growth in a tapered undulator.

In this paper we analyze for the first time the frequency multiplication scheme for a SASE FEL. Simulations using the time-dependent code FAST [12], upgraded for the simulation of higher harmonics, provide a “full physics” description of the process. We illustrate the operation of the proposed frequency doubler for the parameters of the TTF FEL. The result of our study is that a frequency doubler can be implemented at the TESLA Test Facility. With an additional, 13.5 m long undulator (with 1.95 cm period and 0.39 T peak magnetic field), the TTF FEL would be able to produce radiation down to 3 nm wavelength with an output peak power in the GW range, and with excellent spectral properties. The power of the third harmonic from this device (i.e. at 1 nm wavelength) is still in the ten MW range, exceeding any other pulsed radiation source presently available at 1 nm, and sufficiently high for novel applications. In fact, this device approaches the operating range of the future TESLA XFEL.

The paper is organized as follows. Section 2 summarizes recent updates of the TTF FEL parameters which refer mainly to a smaller local energy spread than it was expected before. Section 3 describes the operation of the frequency doubler scheme. Section 4 discusses the integration of the frequency doubler scheme into the TESLA Test Facility. Appendixes 1 and 2 contain information on alternative ways for attaining 3 nm wavelength at the TTF FEL using a uniform undulator and an after-burner, respectively.
A soft X-ray SASE FEL will be commissioned as a user facility in 2004 at the TESLA Test Facility at DESY, covering the wavelength range down to 6 nm. The first description of the TESLA Test Facility FEL has been written in 1995 [1]. An update of the TTF FEL design was fixed in 2002 [2]. The main issues were the change of the undulator focusing structure (separated instead of integrated) and the bunch compression system (removing the low-energy bunch compressor and introducing a RF structure operating at the 3rd harmonic).

![Fig. 2. Schematic layout of the soft X-ray SASE FEL at TTF, Phase 2](image)

Table 1

| Parameters of electron beam at TTF                        |
|-----------------------------------------------------------|
| **Energy**       | 1000 MeV            |
| **Peak current** | 2.5 kA              |
| **Normalized rms emittance**                            | $2\pi$ mm-mrad       |
| **rms energy spread**                                   | 0.2 MeV             |
| **rms bunch length**                                    | 50 $\mu$m           |
| **External $\beta$-function**                           | 4.5 m               |
| **rms beam size**                                       | 68 $\mu$m           |

Table 2

| Nominal parameters of the TTF FEL, Phase 2 for 6 nm wavelength. |
|---------------------------------------------------------------|
| **Undulator**                                                |
| Type              | planar             |
| Period            | 2.73 cm            |
| Gap               | 12 mm              |
| Peak magnetic field | 0.47 T           |
| Segment length    | 4.5 m              |
| **Coherent radiation**                                      |
| Wavelength        | 6 nm               |
| Saturation length | 18 m               |
| Peak power        | 2 GW               |
| Bandwidth (FWHM)  | 0.4%               |
| Pulse duration (FWHM) | 200 fs       |
The analysis of recent experimental results obtained at the TTF FEL, Phase 1 [13] led to the idea that the value of the local energy spread is significantly less than it was expected originally. Only a small value of the local energy spread allows one to obtain a high-peak value of the bunch current after a single bunch compressor. Direct measurements of the local energy spread gave an upper estimate below 5 keV at a beam current of about 100 A [14]. An extrapolation of this experimental result to the project value of 2500 A beam current gives an estimate for the local energy spread of about 100 keV. This is in agreement with recent start-to-end simulations of the bunch in the TTF linac [15,16] predicting the value of the local energy spread within the lasing part of the bunch to be well below 200 keV (see Fig. 3). Note that the original project value for the local energy spread was 1 MeV [1,2]. The local energy spread is one of the essential parameters influencing the FEL operation, and we have to analyze which impact it may have on the operation of the current version of the TTF FEL and its future developments.

Tables 1 and 2 show an updated list of parameters for the SASE FEL at the TESLA Test Facility at DESY. The decrease of the local energy spread results in shorter a saturation length as it is seen in Fig. 4. This is a consequence of the fact that the previous design did not have sufficient safety margin with respect to the energy spread. Figure 5 shows the time and spectral structure of the radiation pulse for the linear and saturation regime.

With a small value of the local energy spread we fall in a different region of physical...
Fig. 4. Energy in the radiation pulse versus undulator length. Nominal beam parameters for the TTF FEL, Phase 2 (see Tables 1 and 2). The radiation wavelength is equal to 6 nm. The dashed line corresponds to the originally planned value.

Fig. 5. Time structure (left column) and spectral structure (right column) of the radiation pulse for an undulator length 12.3 m (linear regime) and 18 m (saturation). Nominal beam parameters for the TTF FEL, Phase 2 (see Tables 1 and 2). The radiation wavelength is equal to 6 nm. The dashed line shows the bunch profile.
parameters which reveals a possibility to implement different FEL amplifier schemes. In particular, the application of dispersion sections for beam bunching becomes very effective.

3 Operation of a frequency doubler

In this section we illustrate the operation of the frequency doubler for the parameters of the TTF FEL, Phase 2. The beam parameters are given in Table 1, and the parameters of the doubler undulator and the dispersion section are listed in Table 3. The resonance wavelength in the main X-ray undulator is equal to 6 nm, and the doubler undulator is tuned to the resonance wavelength of 3 nm.

The frequency doubler scheme operates as follows. The electron bunch enters the main X-ray undulator and produces SASE radiation at the wavelength of 6 nm. During the amplification process the radiation power grows exponentially with the undulator length. Simultaneously, the energy and density modulation of the beam are growing. At the end of the X-ray undulator the beam energy modulation is comparable with the local energy spread. In the present example this takes place at an undulator length of 12.3 m. The output characteristics of the radiation are illustrated with plots in Fig. 5 (upper row). The upper left plot in Fig. 6 shows the phase space distribution of particles for the slice corresponding to 330 fs time coordinate along the bunch. Such a picture is typical for every spike. We see that the modulation amplitude at the second harmonic is small (see lower

| **Parameters of the frequency doubler for the TESLA Test Facility FEL** |
|-------------------------------------------------|
| **Undulator (1st harmonic)**                     |
| Type                                            | planar                                                      |
| Period                                         | 2.73 cm                                                     |
| Gap                                            | 12 mm                                                       |
| Peak magnetic field                            | 0.47 T                                                       |
| Segment length                                 | 4.5 m                                                       |
| Undulator length                               | 13.5 m                                                      |
| **Dispersion section**                          |
| Net compaction factor                          | 1.5 μm                                                       |
| **Undulator (2nd harmonic)**                   |
| Type                                           | planar, tapered                                             |
| Period                                         | 1.95 cm                                                     |
| Gap                                            | 10 mm                                                       |
| Peak magnetic field                            | 0.39 T                                                       |
| Segment length                                 | 4.5 m                                                       |
| Undulator length                               | 13.5 m                                                      |
| Undulator tapering                             | -0.14%/m                                                    |
| **Coherent radiation**                         |
| Wavelength                                     | 3 nm                                                        |
| Energy per pulse                               | 180 μJ                                                      |
| Peak power                                     | 1.5 GW                                                      |
| Bandwidth (FWHM)                               | 0.2%                                                        |
| Pulse duration (FWHM)                          | 130 fs                                                      |
left plot in this figure). On the other hand, there is visible energy modulation with an amplitude of about the value of the local energy spread. When the electron bunch passes through the dispersion section this energy modulation leads to effective compression of the particles as it is illustrated with plots in the right column in Fig. 6. When the bunched beam enters the undulator tuned to the second harmonic, it immediately starts to produce powerful radiation at the second harmonic. That is important, but not the main feature of our proposal. Let us study more closely the phase space distribution of the particles at the exit of the dispersion section. We see that this distribution is double-periodic with respect to the second harmonic. I.e., only each second bucket is populated with particles. If we trace the evolution of the FEL process in the uniform undulator, we find that “thermalization” takes place. The population of particles in the originally filled buckets is reduced, and some of these particles travel into the ponderomotive well of originally empty buckets. Simultaneously, the energy spread in the bunch grows due to the FEL process. Finally, saturation occurs, and the properties of the radiation are close to those described in Appendix 1.

Thus, another key idea of our proposal is to preserve the original bunching of the beam and to organize an effective extraction of the energy from the electron beam. This idea is simply realized by using a tapered undulator. The process of amplification proceeds
Fig. 7. Energy in the radiation pulse versus undulator length in the frequency doubler.

Fig. 8. Time structure (left column) and spectral structure (right column) of the radiation pulse at a length of the frequency doubler of 9 and 13.5 meters. The radiation wavelength is equal to 3 nm. The dashed line shows the bunch profile.
as follows. The bunched beam (double-periodic) produces strong radiation from the very beginning because of the large spatial bunching. The strong radiation field produces a ponderomotive well which is deep enough to trap particles, since the original beam is relatively cold. The radiation produced by these captured particles increases the depth of the ponderomotive well, and they are effectively decelerated. The undulator tapering preserves the synchronism of trapped particles and radiation, and a significant fraction of the energy can be extracted. Simulations using the time-dependent FEL code FAST [12] confirm this qualitative picture. Figure 7 shows the evolution of the energy in the radiation pulse in the tapered undulator. Despite of the original spiking seeding the process of the second harmonic (see Fig. 6), we effectively trap a significant fraction of the particles, and can achieve much higher power than for the case of an untapered undulator (see Appendix 1). Figure 8 shows the temporal and spectral structure of the radiation pulse after 9 and 13.5 meter of second-harmonic undulator. One can see that the radiation pulse length is about a factor of two shorter than that of a traditional SASE FEL (see Fig. 10). This is a consequence of the nonlinear transformation provided by the dispersion section. Another important feature of the radiation from a tapered undulator is the significant suppression of the sideband growth in the nonlinear regime (compare Figs. 8 and 10). This means that in the proposed scheme the spectral brightness of the radiation is increased proportionally to the radiation power. In the case of a uniform undulator the peak brightness is reached at the saturation point and is then reduced due to the sideband growth [17].
The TTF FEL is a pioneer user facility in the VUV and soft X-ray wavelength range. The conceptual design was first elaborated in 1995 [1]. At that time only a single-pass SASE FEL was considered. In 1998 it was decided to upgrade the TTF FEL by a seeding option [18,19]. Other possible extensions of the TTF FEL user facility making use of some space left behind the main FEL undulator have been discussed [20].

This free space downstream of the main undulator (see Fig 2) would be sufficient for a 9 meter long (2 × 4.5 m sections) second harmonic radiator. It is planned now that the main X-ray undulator will consist of six sections. This is mainly dictated by the wish to have sufficient safety margin during the first commissioning of the SASE FEL. However, our analysis in the present paper shows that for the expected electron beam parameters five undulator modules will be more than sufficient. This means that in the future there will be space for three modules of the frequency doubler. This will allow to realize the full frequency doubler and to extend the wavelength range of the TTF FEL down to 3 nm with GW-level power without changing the present TTF layout. Additional hardware to be manufactured is a dispersion section and a 13.5 m long undulator. Since the required strength of the dispersion section is small, its design may be similar to that of a phase shifter for the X-ray SASE FEL [21]. It will also be necessary to include a linear tapering of 0.14%/m (in the 13.5 m long undulator with 1.95 cm period and 0.39 T peak magnetic field. This does not appear to be a serious problem. In conclusion we can state that these are minor expenses in view of the significant extension of the capabilities of the TTF FEL user facility.

5 Conclusion

In this paper we have described an effective frequency doubler for SASE FELs. For the first time the frequency multiplication scheme has been analyzed for SASE FELs. To be specific, we have illustrated the proposed FEL scheme using the parameters of the TESLA Test Facility. It is shown that a frequency doubler allows to reach the water window and to produce GW-level radiation pulses. It is important to note that a frequency doubler would be well compatible with the seeding option, and would transfer all the advantages of the seeding option to twice the photon energy [18,19]. In general, the frequency doubler scheme has several significant advantages over traditional SASE FELs with uniform undulators:

- shorter total magnetic length;
- a possibility to attain higher output power and brightness of the radiation;
- shorter radiation pulse duration.

The realization of a frequency doubler at the TTF is considered as extremely important not only for reaching the water window. It may also be relevant for realizing the X-ray FEL user facility in the 0.1 nm range. The use of frequency doublers at a large-scale facility could result in a significant reduction of the project costs. In addition, the safety margin for facility operation becomes more relaxed.
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Appendix 1: 3 nm option with uniform undulator

The maximum energy of the TTF linac is limited to 1 GeV. The present TTF undulator has a period of 2.73 cm and a peak magnetic field of 0.47 T which limits the minimum wavelength to 6 nm. In principle, one can consider a scenario of constructing a short-period undulator allowing to generate wavelengths down to 3 nm. Such an option was not studied previously because of the large value of 1 MeV for the expected local energy spread. However, in view of the change of this parameter it seems to be reasonable to perform such a study in order to have a possibility for comparison of different approaches for attaining 3 nm wavelength. This section illustrates the option of a 3 nm SASE FEL with a uniform undulator. The parameters of the electron beam are presented in Table 1, and those of the undulator are given in Table 4.

Figure 9 shows the evolution of the energy in the radiation pulse along the undulator. The growth of the radiation energy starts to saturate at an undulator length of about 36 m, and the radiation energy is about 100 $\mu$J. Further increase of the undulator length leads to a slow increase of the radiation energy, while the spectral width is increased due to sideband growth in the nonlinear regime (see Fig. 10).

Table 4
3 nm option with uniform undulator

| Undulator                  |          |
|----------------------------|----------|
| Type                       | planar   |
| Period                     | 1.95 cm  |
| Gap                        | 10 mm    |
| Peak magnetic field        | 0.39 T   |
| Segment length             | 4.5 m    |
| Undulator length           | 36 m     |
| Coherent radiation         |          |
| Wavelength                 | 3 nm     |
| Energy per pulse           | 100 $\mu$J |
| Peak power                 | 500 MW   |
| Bandwidth (FWHM)           | 0.2%     |
| Pulse duration (FWHM)      | 230 fs   |
Fig. 9. Energy in the radiation pulse versus undulator length for a 3 nm option with uniform undulator.

Fig. 10. Time structure (left column) and spectral structure (right column) of the 3 nm radiation pulse for a uniform undulator at a distance of 36 and 40.5 meters. The dashed line shows the bunch profile.
An option of second harmonic generation at TTF FEL using an after-burner has been under discussion for several years [22]. Here we present the results of time-dependent simulations of the after-burner scheme. The parameters of the electron beam are given in Table 1, and the parameters of the undulator and the output radiation are presented in Table 5.

In the after-burner scheme the spent electron beam leaving the main X-ray undulator passes an undulator tuned to the second harmonic. At the exit of the main undulator the electron beam has a pronounced amplitude of density modulation at the second harmonic which serves as input signal for the second-harmonic undulator (see Fig. 11). When the electron beam enters the after-burner radiator, it readily starts to produce radiation. However, the power growth saturates quickly at 2 meters, as it is seen from Fig. 12. This is due to the large energy spread induced in the main undulator (see Fig. 11). Figure 13 presents the temporal and spectral structure of the radiation pulse at the exit of the after-burner. We find that the FWHM pulse duration is relatively large, about 250 fs. The spectral width is also large, about 0.4%, and is driven by the FEL process in the main undulator. Finally, the level of output radiation power is low, about 60 MW, i.e. about 3% of the power of the fundamental frequency of the main undulator. Remembering that SASE radiation from a planar undulator at saturation always contains the 3rd harmonic at a per cent level, we conclude that harmonic generation using an after-burner does not provide extra opportunities for user applications.

Table 5

3 nm option with after-burner

| Undulator       |          |
|-----------------|----------|
| Type            | planar   |
| Period          | 1.95 cm  |
| Gap             | 10 mm    |
| Peak magnetic field | 0.39 T  |
| Undulator length | 2 m     |
| Coherent radiation |        |
| Wavelength      | 3 nm     |
| Energy per pulse| 15 µJ    |
| Peak power      | 60 MW    |
| Bandwidth (FWHM)| 0.4%    |
| Pulse duration (FWHM) | 250 fs |
Fig. 11. Phase space distribution of the particles in a slice (left plot) and amplitude of the second harmonic (right plot) at the exit of the main undulator radiating at 6 nm wavelength. The SASE FEL operates at saturation. Nominal beam parameters for TTF FEL, Phase 2 (see Table 2) have been used for the simulation. The dashed line shows the bunch profile.

Fig. 12. Energy in the radiation pulse versus undulator length in the after-burner. The radiation wavelength is equal to 3 nm.

Fig. 13. Time structure (left plot) and spectral structure (right plot) of the 3 nm radiation pulse for a 2 m long after-burner. The dashed line shows the bunch profile.
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