DEVELOPMENTS IN CASCADED HGHG-FELs*

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Abstract

Seeding in combination with frequency up-conversion is widely recognized as a method to provide FEL radiation with properties superior to the output of a SASE FEL. As one of the first frequency up-conversion schemes the High Gain Harmonic Generation (HGHG) has successfully been demonstrated in Brookhaven [1] and was proposed for the BESSY Soft X-ray FEL [2]. Several alternative schemes based on HGHG have been proposed during the last years. This paper discusses and compares these proposals to the original cascading of HGHG-stages including the fresh bunch technique.

INTRODUCTION

A Free Electron Laser (FEL) utilizing the principle of High Gain Harmonic Generation is composed of at least two undulators separated by a dispersive section. The electrons resonate with the electromagnetic field of a seed laser, while they pass the first undulator, called modulator. An energy modulation at the seed wavelength is induced. In a very long modulator, this energy modulation would turn into a density modulation, called bunching, due to the dispersion of the undulator, but also the induced energy modulation, $\Delta\gamma$, and the incoherent energy spread, σ_γ, due to spontaneous synchrotron radiation would grow with increasing undulator length. Both would lead to an increase of the effective energy spread which is given by

$$\sigma_{\gamma,tot} = \sqrt{\sigma_\gamma^2 + \frac{\Delta\gamma^2}{2}}. \quad (1)$$

The longitudinal velocity spread scales with the effective energy spread, implying longer gain lengths and a reduced peak power. Thus, the effective energy spread reduces the FEL amplification. A dipole chicane can provide for the necessary dispersion without increasing the effective energy spread too much. The density modulation in the electron bunch after the dispersive section includes a high number of harmonics. When the prebunched beam enters the second undulator, tuned to a harmonic of the seed wavelength, it will immediately radiate on the harmonic wavelength, and the FEL process develops. The second undulator is called radiator.

This principle has been demonstrated in Brookhaven in 2001. It has been shown that the seed laser properties, such as the pulse length and pulse shape, are transferred to the output pulses, which show a high degree of reproducibility and temporal as well as spectral purity, superior to SASE FEL pulses [3]. Further pioneering experiments have been conducted over the years, demonstrating super radiance, dispersion tuning, chirped pulse amplification and the like [4, 5, 6].

Due to the limitations in the seed laser wavelength and the necessary restriction to the usage of the lower harmonics ($n \leq 5$) in the HGHG stage, already in 2001 cascading of HGHG stages has been proposed [7] in combination with the fresh bunch technique [8]. While the output pulse of the radiator is well suited to seed another modulator, the seeded part of the electron bunch is too heated after the passage through the radiator to be seeded again. It is possible though, to delay the electron bunch, such that the radiation pulse interacts with a part of the bunch that has not been seeded.

Although the cascading of HGHG stages has not yet been demonstrated, proposals like the BESSY FEL or FERMI [9] are based on this principle. The most pronounced difficulty related to cascading is the necessity of long bunches and high bunch charges. Therefore, alternatives have been proposed during the last years, mainly to avoid the fresh bunch technique.

In this paper, we present a comparison of three cascading schemes such as the modulator and radiator cascades, the split modulator and the radiator cascades using super radiant pulses. In order to evaluate and compare the advantages of these new ideas they have been applied to two test cases. For the modulator and radiator cascades and the split modulator, the BESSY Low Energy (LE) FEL has been chosen. It is close in energy and wavelength to the two proposals and could easily be adapted. As the alternative approaches do not include the concept of a final amplifier, for the comparison the BESSY LE-FEL is ended after the last radiator. For the super radiant pulse, the STARS layout [10] has been selected. For the simulation studies the 3D-time dependent FEL-code GENESIS 1.3 [11] has been used.

MODULATOR AND RADIATOR CASCADES

In the WiFEL proposal [12], modulator cascades in combination with radiator cascades have been introduced. Before entering a regular HGHG stage, shifting the wavelength from 20 nm to 4 nm, the bunch passes an additional modulator, that is seeded by a 40 nm HHG [13] seed (modulator cascade). The seed power is kept low in order to limit the induced energy modulation. A dispersive section boosts the bunching on the second harmonics. The pre-

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bunched beam enters a regular HGHG stage using the 5^{th} harmonic. After an additional dispersive section a second radiator is tuned to the 3^{rd} harmonic at $1.37nm$ (radiator cascade). As the energy spread is kept low and seeding happens only once, the necessity of a fresh bunch part is avoided.

Modulator Cascade

There is a fundamental difference between the first and the second modulator in a modulator cascade. In the first modulator, the energy modulation is introduced by the radiation from the laser seed. The energy modulation increases rapidly and can then be transferred into spatial bunching in the following dipole chicane. In the second modulator the prebunched beam is not resonant anymore to a strong seeding field. The energy modulation and thus the bunching evolve slowly, because only little radiation is emitted, as the bunching rate is moderate. Therefore, it takes many undulator periods to restart the FEL process and develop bunching.

In the BESSY LE-FEL, the relative energy spread of $2 \cdot 10^{-4}$ raises to $1.5 \cdot 10^{-3}$ in the modulated bunch part, using a seed peak power of 500 MW. The bunching on the 5^{th} harmonic at the end of the modulator, of less than 0.1%, is boosted to 30 % by the dipole chicane.

Using a modulator cascade for BESSY LE-FEL a seed power of 100 MW and a 15 period second modulator are necessary to induce enough energy modulation to obtain 25% bunching on the fundamental of the second modulator. The wavelength of the seeding radiation is choosen such that the 5^{th} harmonic of the second modulator is the same as the final wavelength of LE-FEL, i. e. 10 nm.

For a reasonably long second modulator ($\leq$ 2 m), the bunching on the fundamental is not much increased. The bunching on the 5^{th} harmonic though, develops due to the dispersion in the undulator which is high enough for the harmonic. The relative (effective) energy spread remains low, around $6 \cdot 10^{-4}$. Due to the little energy modulation, the following dipole chicane is ineffective: no more than a factor of two can be gained. Consequently, the initial bunching achievable at the beginning of the radiator is only a few %, compared to 30% for the original HGHG cascade, making very long radiators necessary.

Note that the amount of bunching produced on the 5^{th} harmonic strongly depends on the energy spread, Fig. 1. For an initial relative energy spread $2 \cdot 10^{-4}$, no seed information is transferred to the radiator, and SASE develops. However, a successful modulator cascading is possible for smaller relative energy spreads. The temporal and spectral radiation output for the modified BESSY LE-FEL with a relative energy spread of $8 \cdot 10^{-5}$ is shown in Fig. 2 (red curve). The low initial energy spread explains the lower noise level compared to the two stage HGHG output, but it does not enhance the output at the desired wavelength.

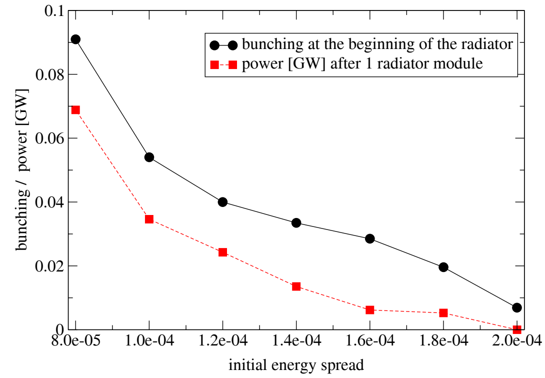

Figure 1: The bunching achievable at the beginning of the radiator (black) depends on the initial energy spread. The power emitted after one radiator module (red) shows the same dependency.

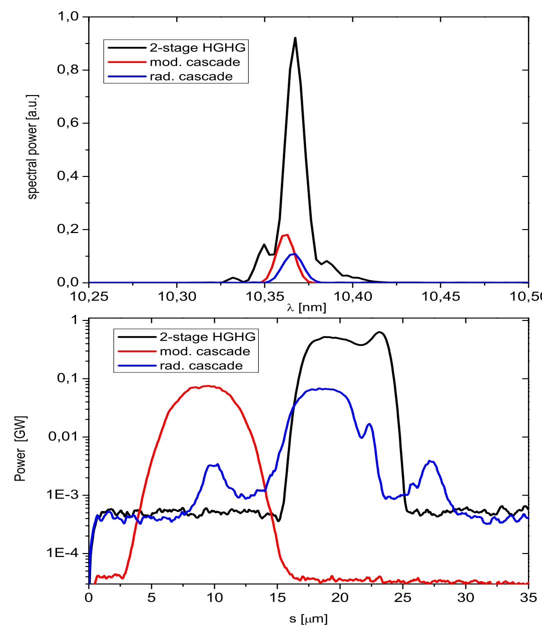

Figure 2: The output of the last radiator of the BESSY LE-FEL (black), and the corresponding radiator (blue) and modulator (red) cascades. The low initial energy spread necessary for the modulator cascade causes the lower noise level.

Radiator Cascade

Similar to the second modulator in a modulator cascade, also in the undulators of a radiator cascade the new energy modulation and thus the increase of the harmonic bunching have to be developed by the beam itself. The only difference is that the radiators are longer, thus the radiation becomes stronger and consequently the energy modulation grows. Obviousely, the second radiator suffers from the effective energy spread generated in the first one and also the effect of the dispersive section is limited, as Fig. 1 suggests.

In spite of the small initial relative energy spread of $8 \cdot 10^{-5}$, radiator cascading in combination with a modulator cascade, as suggested in [12], is not applicable for the BESSY LE-FEL. Even for a long first radiator of ≈ 9.5 m the fundamental bunching remains around 8 %. Only a maximum bunching of 2 % could be achieved on the fifth harmonic. This small bunching in combination with the for this process too high relative (effective) energy spread of $6 \cdot 10^{-4}$ prevents the development of the FEL process in the second radiator.

However, radiator cascading can succeed following a regular HGHG stage where the initial bunching on the radiator fundamental is much higher. Fig. 2 compares the output of the last radiator of the two stage HGHG-FEL with the output of the corresponding radiator and modulator cascades. The radiation pulse becomes longer due to slippage and side peak develop.

SPLIT MODULATOR

For the FERMI project the idea of a split modulator [14] is considered. The first part of the modulator is seeded with a very strong radiation field, in order to develop a large harmonic content in the density modulation. The resulting high energy modulation is reduced by shifting the ponderomotive phase between the beam and the seeding field by 180° in front of the second part of the modulator. Due to the phase shift, electrons that gained energy in the first modulator will now loose energy, and vice versa, so that a net decrease in the energy modulation is achieved. Due to the dispersion in the second undulator, the harmonic content in the density distribution keeps increasing, so that the wavelength conversion to much higher harmonics seems feasible, avoiding a second HGHG stage.

However, short pulse lengths of a few tens of femtoseconds, in combination with slippage lead to a remarkable variation of the seeding power experienced by the electrons in the two parts of the split modulator. This significantly degrades the efficiency of this approach. As shown in Fig. 3, the reduction of the effective energy spread is much lower for the short pulse than for the CW pulse. In spite of the decreasing energy modulation the effective energy spread after the split modulator remains higher than after a regular two stage HGHG cascade with fresh bunch technique.

For the simulation studies, the ninth harmonic of a 459 nm seed is generated with the regular two stage BESSY LE-FEL, i.e. using twice third harmonic, as well as with the ninth harmonic of the seed in one stage using the split modulator approach. The output power of such a split modulator cascade is lower, as shown in Fig. 4 when using the same radiator.

In addition, when going to very high harmonics ($n \geq 10$), as suggested in [14], most of the charge is concentrated in only every n^{th} bucket at the entrance of the radiator. Especially for low currents and high bunching factors the radiation amplification is retarded. This is topic of further investigations.

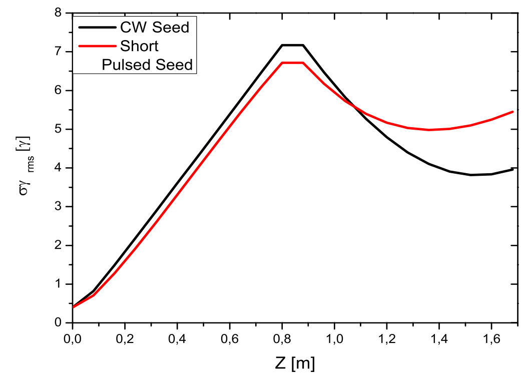

Figure 3: Due to the slippage, the reduction of the effective energy spread is much lower for the short pulse (red) than for the CW pulse (black).

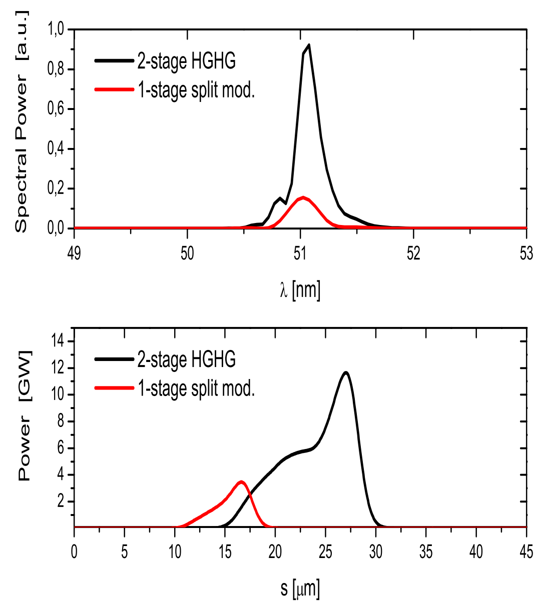

Figure 4: The output power of a split modulator (red) cascade compared with a corresponding regular two stage HGHG cascade (black).

SUPER RADIANT PULSE IN RADIATOR CASCADES

Also the SPARC project [15] favours a high seed power. The goal is to almost reach saturation in the bunching at the exit of the modulator. In the following radiator the pulse reaches the super radiant regime [16] quickly. In this regime, the emitted power is strong enough to instantly modulate the energy of electrons ahead of the pulse. This way, the different phases of the FEL process, energy mod-

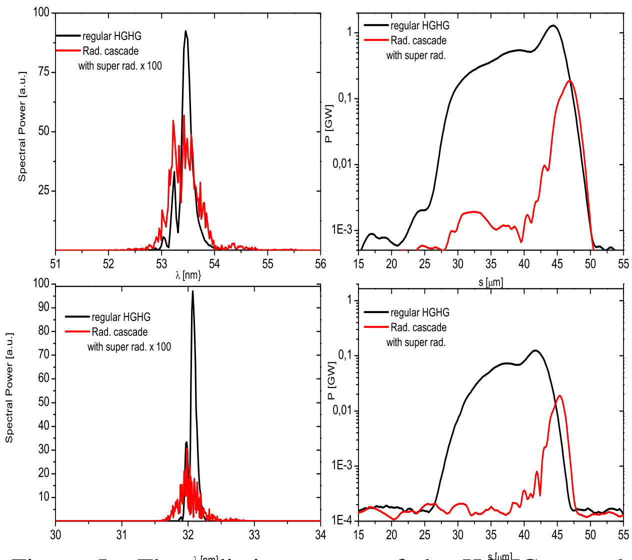

Figure 5: The radiation output of the HGHG cascade (black) and the super radiant cascade (red) are depicted. As expected, the spectral quality (left) degrades for the very short super radiant pulse.

ulation, bunching, and debunching all happen simultaneously at different locations in the bunch. While the electrons correlated with the leading flank of the pulse build up the bunching, maximal bunching is reached for electrons at the peak location of the pulse. Electrons in the rear of the pulse are already debunched. Bunching on the harmonics occurs faster than on the fundamental. So, at the location of leading flank of the pulse there are electrons that are maximally bunched on any harmonic wavelength. It is now possible to simply pass the super radiant pulse to an undulator tuned to a harmonic and the super radiance will be preserved at the shorter wavelength. Due to the fast propagation of the super radiant pulse over the electron beam, the fresh bunch technique is practically built in. The bunch has to be long enough to accommodate the slippage, but remains shorter than in successive HGHG stages. In addition, the super radiant pulses are extremely short and of extensive power.

For the present studies, the first modulator of STARS is seeded with such a high seed power that the pulse generated in the following STARS first radiator reaches the super radiant regime very quickly. After the dispersive section, the prebunched electron beam is passed to the second radiator which is tuned to the third or fifth harmonic of the first radiator. In Fig. 5, a comparison of the output qualities of the two stage HGHG cascade and the super radiant cascade is depicted after one radiator module. As expected, the spectral quality degrades for the very short super radiant pulse. The maximum achievable power in this setup is lower as the effective energy spread of the radiating bunch part in the case of the super radiant cascade is a factor of four higher.

CONCLUSION

Three newly proposed cascading schemes for frequency up conversion were compared to the classical HGHG cascades proposed for the BESSY FEL and for STARS. None of the new schemes succeeds in keeping the effective energy spread as small as the fresh bunch technique. Consequently, the achievable output power is lower in the new approaches when comparable hardware is used, and the signal to noise ratio is reduced. While the modulator cascade essentially depends on a very small initial energy spread, the radiator cascade can handle higher value but still suffers from the effective energy spread accumulated during the proceeding cascade. The benefits of the split modulator approach grow with longer seed pulses. The super radiant cascades offer the shortest pulses at the expense of spectral purity. Any of the proposed schemes could be beneficial when suitable beam parameters (e.g. energy spread) can be achieved, or the user demands are appropriate (ultra short pulses, no demand for spectral purity). For the BESSY FELs and user demands no significant improvement could be found.

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