R&D EXPERIMENTS AT BNL TO ADDRESS THE ASSOCIATED ISSUES IN THE CASCADING HGHG SCHEME

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Abstract

Several experiments that can be carried out at BNL's DUVFEL are discussed to address issues associated with cascaded HGHG FELs. These include: Chirped Pulse Amplification (CPA), HGHG with seed shorter than electron bunch length, 8th harmonic HGHG (from 800 nm to 100 nm), regenerative synchronization of seed pulse and electron bunch, tuning of HGHG without changing seed, and cascading from 400 nm to 100 nm to 50 nm using NISUS and VISA undulators. These experiments may have important impact on the development of multi-stage cascaded HGHG FELs.

INTRODUCTION

The proof-of-principle HGHG experiment at 5 μm [1,2] and recent HGHG experiment at the DUVFEL [3] have generated significant interests in the FEL community. The more relaxed requirement on electron beam current and emittance to generate coherent deep UV output with much narrower bandwidth and high pulse energy stability, as exhibited by the recent experiment, and its potential to be generalized to soft-x-ray FEL, have attracted much attention. Several labs[4], including BESSY [5], ELETRRA [6], LBL [7], MIT [8], and SSRF [9] proposed the development of UVFEL based on HGHG principle or soft-x-ray FEL based on the cascaded HGHG principle [10,11,12]. Among them SSRF has already started the construction of an FEL system based on the HGHG principle. Hence it would be a contribution to be able to carry out a first proof-of principle experiment of cascaded HGHG at the DUVFEL. In this paper, we discuss this experiment and several associated experiments that can be carried out at BNL before this experiment and may also have important impact on the development of multi-stage cascaded HGHG FELs.

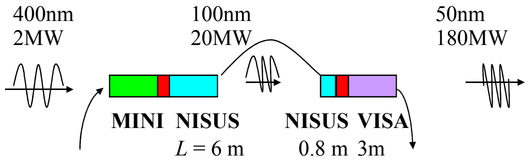

Figure 1: Cascading HGHG using Fresh Bunches under the present e-beam conditions, see Table 1, and a seed pulse with a duration of 200 fs.

THE CASCADED HGHG DEMONSTRATION EXPERIMENT AT DUVFEL

The analysis of recent experiment at DUVFEL shows that it is possible to realize a proof-of-principle cascaded HGHG experiment with existing system parameters and with reasonable cost, as we shall show in the following. This suggested experiment is a cascaded HGHG with two stages. In the future it is possible to generalize it to several stages by other labs. We will also show that even though the DUVFEL is a small facility, with present electron beam parameters and without significant increment of hardware, we can carry out experiments to address several important issues associated with the cascaded HGHG FEL.

Table 1: Present electron beam conditions.

Peak current	I	300	A
Bunch duration	σ_t	1	ps
Beam energy	E	288	MeV
Energy spread	σ_γ/γ	1×10^{-4}	
Norm. emittance	$\varepsilon_{n,xy}$	2.7	π mm mrad

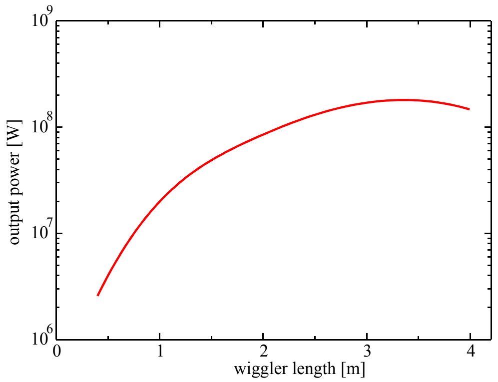

Figure 2: TDA simulation of the last stage of a cascading HGHG from 400 nm, to 100 nm, to 40 nm for a beam current of 500 A and a seeding at 100 nm of 20 MW.

A cascaded HGHG FEL with two stages is schematically shown in Figure 1. More detailed description of the principle of the cascaded HGHG is given in [10]. In this experiment we propose to use the first 6 meters of the existing NISUS undulator to achieve output at 100 nm using a 400 nm seed into the existing MINI undulator. When compared with the recent published PRL paper [3], it is easy to see that the parameters in the proposed experiment, electron beam current (300 A), energy spread (1×10^{-4}), pulse length (1ps), and emittance (2.7 μm) are the same as we have already established by the recent results [3]. The electron beam energy is to be increased from the present 200 MeV to 288MeV. Simulation shows that when seeded with a 2-MW 400-nm 200-fs laser-pulse, the 100 nm stage will reach beyond 20MW with this set of parameters in 6 m (the recent experiment show saturation to 100MW in 5 m, at 266 nm), but we can always control the output at the desired 20MW level, for example by tuning the dispersion magnet before the NISUS away from maximum bunching, or use a part of the electron bunch with less current than 300 A. Following the 6 m NISUS is a shifter chicane (about 0.3-0.4 m long), which will shift the 100 nm output 200 fs pulse to a "fresh" part of the electron bunch. This is followed by a 0.8 m long NISUS section as a modulator for the next stage of HGHG, and then by a dispersion magnet (about 0.3-0.4 m long). The dispersion magnet will transform the 100 nm energy modulation into micro-bunching, which will generate coherent radiation at 50 nm and will be exponentially amplified to saturation at 180 MW power in the 3-m long VISA undulator following this dispersion magnet.

Here we assume 300 A for the beam current, so the saturation is at 3 m in the VISA undulator. Within 2 meters the output is only about a factor 2 from saturation, as shown by Figure 2. Recently a tomography [13] at our DUVFEL has shown that after compression the peak current is more than 400 A, as is shown in Figure 3 (see the current profile at the right side of the figure). In near future, we will improve the peak current to more than 500 A, and the saturation can be reached at 2 meters in VISA. At the present, we have already the parts for a 2-m long VISA undulator, hence this will significantly lower the cost of the project.

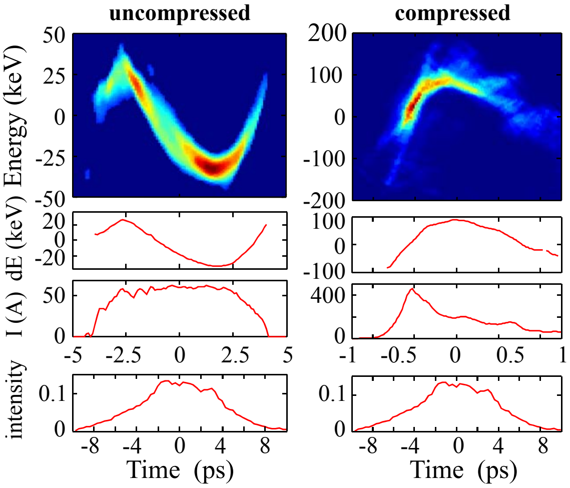

Figure 3 Tomography of the electron bunch distribution for a uncompressed (left) and compressed (right) bunch [13].

Another important issue in the cascading scheme is the time jitter between the electron bunch and the seed laser. It is important that the jitter should be much less than the electron bunch length. As a recent experiment using electro-optical method [13] showed, the jitter is about 300 fs FWHM. To see the relation between the cascaded FEL laser pulse and the electron pulse, we plot them in Figure 4 against the background of the current profile obtained by the tomography in Figure 3. This figure shows that with the jitter about 300 fs, it is still possible to arrange the seed pulse and the cascaded pulse so that the first HGHG operates at about 200 A while the second HGHG stage uses the peak of more than 400 A. Therefore our analysis shows clearly the feasibility of this experiment, which is based on the existing system parameters.

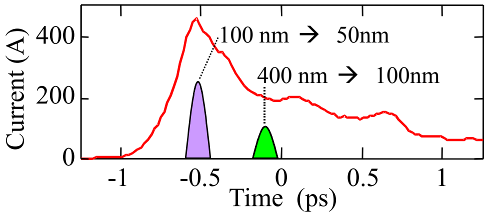

Figure 4: Illustration on double use of an electron bunch in a cascaded HGHG setup.

It is also clear that the space needed by this experiment is available because we only need 6 meters NISUS for the first HGHG stage. The present NISUS is 10 m long, hence leaving 4 meters room for the second stage. In addition, the most important hard ware, the VISA parts, is already in our possession. So the main works for the implementation of this experiment is the removal of the 4 m NISUS and assembly and installation of the 2-m VISA. Hence the total cost is significantly reduced.

Not only the success of the cascaded HGHG experiment provides a first proof-of-principle demonstration, the output of the cascaded HGHG at 50 nm with 180 MW peak power also provides an unprecedented high intensity coherent new light source at this wavelength.

SEVERAL EXPERIMENTS ADDRESSING THE ISSUES ASSOCIATED WITH THE CASCADED HGHG SCHEME

In addition to the cascaded HGHG proof-of-principle experiment, there is also a series of FEL experiments closely associated with it, but in smaller scale, hence can be carried out at DUVFEL earlier. These experiments will significantly improve and advance the multi-staged cascaded scheme. In the following, we shall discuss these experiments: their significances, and their present status.

Chirped Pulse Amplification (CPA)

CPA in FEL can be used to generate high peak power short pulse (bellow 10-20 fs), which will have wide applications in physics and chemistry and also can be used as seed for the multi-staged cascaded HGHG. Because of the high efficiency and wide bandwidth of FEL, CPA using FEL can generate unprecedented short radiation pulses in short wavelength region (bellow 100 nm) [14]. After the recent success of the HGHG experiment at DUVFEL, we have carried out the first step towards a first demonstration of CPA in FEL at 266 nm [15]. As shown in Figure 5, the green bars in the lower part of the figure represent chirped seed with the tail at shorter wavelength, while the blue curved bar represent the electron bunch with three different chirping of energy (with tail at higher beam energy). The three curves in the top figure are the output spectrum for these three settings. The middle one (blue curve) has the largest bandwidth. In the latter setting the electron beam energy chirp matched to the seed with best overlap in the time-energy phase space. In the other two cases there is less matching, which results in a narrower bandwidth. Due to RF curvature, the best overlap occurs at different part of the seed for each case, hence the wavelength is also shifted.

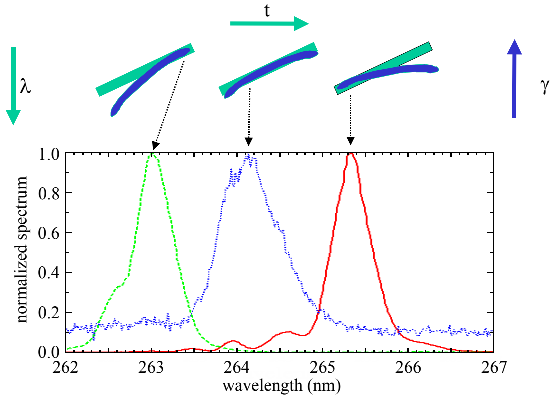

Figure 5: Several CPA HGHG Spectra (bottom). The top part illustrates the explanation for the different spectrums as an effect or the RF curvature. See text for details.

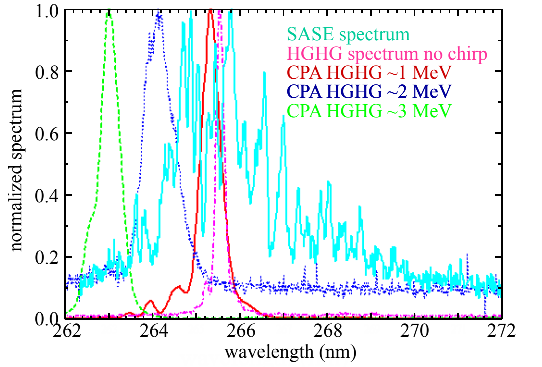

Figure 6: Chirped and unchirped HGHG spectra.

In Figure 6 we plot the 3 spectra with the spectrum of SASE and HGHG without chirp (the pink curve with minimum bandwidth has nearly fourier transform limited bandwidth). It clearly shows the significant increase of the bandwidth for CPA, and the smooth profile of the CPA spectra, compared with the SASE spectrum indicate the well preserved coherence for the CPA output, which is essential for later compression to generate short pulses.

Figure 7 shows the measured bandwidth as a function of the energy chirp of the electron bunch. Since the seed laser bandwidth is 5.5 nm, we expect the CPA with bandwidth of 1.8 nm in idealized situation (our current experiment is carried out in 3rd harmonic of the seed at 800 nm with output at 266 nm, hence the bandwidth is divided by 3 for a perfect CPA condition). The actually achieved bandwidth is 1.5 nm, with future potential of further improved bandwidth more close to 1.8 nm. Based on this data, the expected compressed CPA output pulse length would be about 50 fs or larger, depends on the quality of the preservation of the phase linearity in the HGHG process.

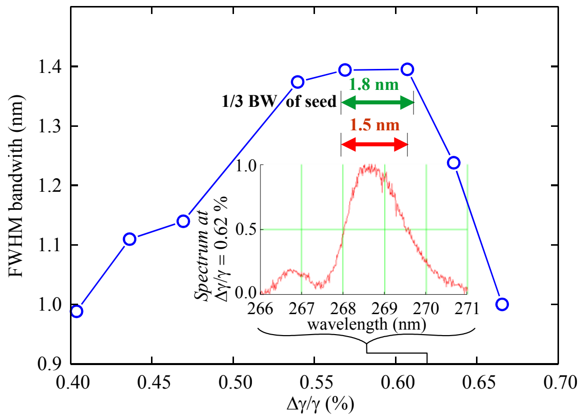

Figure 7: Spectral bandwidth vs Chirp. The inset shows the recorded spectrum at a chirp of 0.62 %.

The next steps in this direction will be the measurement of the preservation of the phase chirp linearity by a method called Spectral Interferometry for Direct Electric Field Reconstruction (SPIDER) [16] and actually carry out the compression as a first demonstration of CPA in FEL. This is now in advanced stage of preparation.

In Figure 8 we show the basic principle of the SPIDER. The 266 nm output pulse is split into two temporarily spaced pulses and mixed with a longer 800 nm chirped pulse and creates two 400 nm pulses. Since the 800 nm pulse is chirped, these two 400 nm pulses not only are spatially separated, but also have their wavelength shifted relative to each other. Hence, when they are sent to a

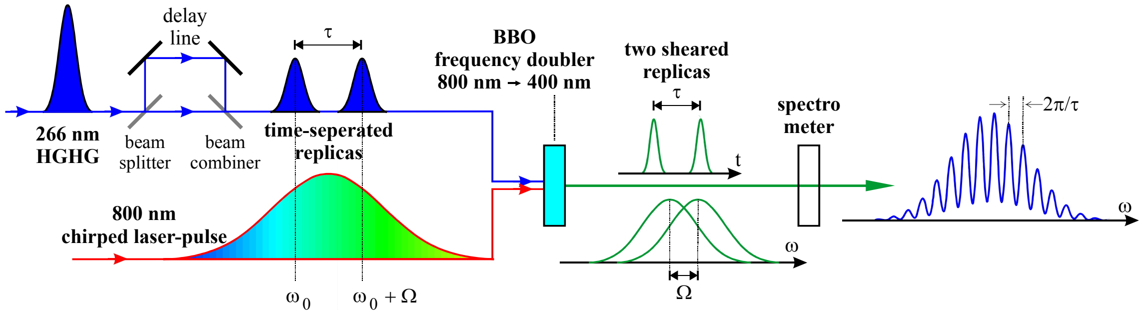

Figure 8: Principle of the SPIDER (Spectral Interferometry for Direct Electric-Field Reconstruction) setup [10].

spectrometer, their spectrum form a interference pattern as show in the upper right corner of the figure. The fringes give information about the relation between the phase and frequency, thus can be used to reconstruct the electric field of the 266 nm pulse.

A first SPIDER measurement result for an unchirped HGHG pulse is shown in Figure 9. It is clear the phase change within the bandwidth is negligible. The measurement on chirped pulse is still under way.

In the future works, it would be challenging and exciting to develop CPA bellow 200 nm, which would be an unprecedented achievement, in particular below 100 nm once our electron beam energy is upgraded to 300MeV.

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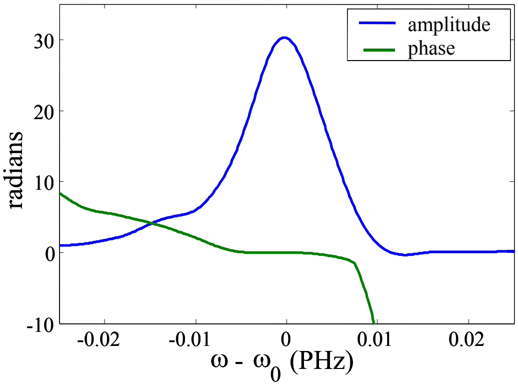

Figure 9: First SPIDER measurement of an unchirped HGHG pulse.

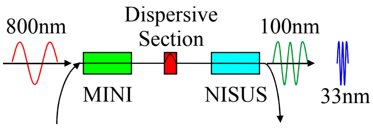

Figure 10: Experimental setup for lasing at the 8th harmonic.

8^{th} harmonic HGHG at DUVFEL

Our present HGHG is in 3rd harmonic, as we have mentioned before. The design was based on data from 10 years ago, and was a conservative one: it was based on the assumption of local energy spread of 1.5×10^{-3}, while our recent experiment showed it is bellow 1×10^{-4}. Based on our new data obtained during the HGHG experiment, we propose to carry out new 8th harmonic HGHG experiment with seed still at 800 nm, but output directly shorten to 100 nm instead of the present 266 nm, as shown in the schematic of Figure 10. The output reaches saturation to 100MW at about 8 m in NISUS, as shown in Figure 11. There will be non-linear harmonic output at 33 nm of about 1 MW, which will have significant applications in chemistry too.

As we mentioned before, the local energy spread is found to be less than 1×10^{-4} during the recent experiment. Actually there are indications that this can be as small as 0.3×10^{-4}. Theory of HGHG predicts that the highest harmonic number is determined by the local energy spread. Hence it means it is possible to reach even higher than 8 for the harmonic number in the future (ours will be limited to 8 by the 300 MeV electron beam energy we plan to upgrade to).

The significance of higher harmonic number in HGHG is that for a cascaded HGHG scheme it means we need fewer stages of HGHG to achieve shorter wavelength. Hence the demonstration of 8th harmonic HGHG will have important impact on future development.

The proposed 8th harmonic HGHG requires only the reduction of vacuum chamber of the present MINI undulator (the 0.8 m modulator before the NISUS) from the present about 4 cm to 2.1 cm, and a minor modification of the corresponding supporting mechanical structure of the undulator. Hence the cost associated with this advance is very low, the required man-power is also very limited.

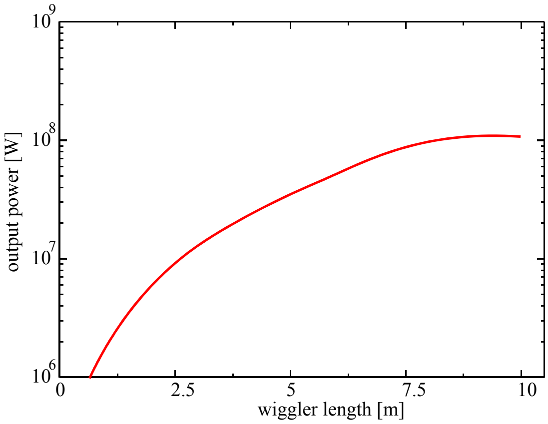

Figure 11: TDA simulation of the power vs distance for 100 nm in HGHG from 800 nm.

Short pulse HGHG

In the present HGHG experiment the electron bunch length is 1 ps, while the seed laser pulse length is 9 ps, as described in the PRL paper [3]. In a cascaded HGHG experiment the pulse length should be much shorter than the electron bunch length. In the proposed cascaded HGHG experiment, we shall use a seed length of 200 fs long. Hence as a first step towards the cascaded HGHG experiment, we shall test one stage of HGHG with 200 fs seed pulse. When the time jitter between the seed and the electron bunch is negligible compared with the electron bunch length, the measurement of the HGHG output

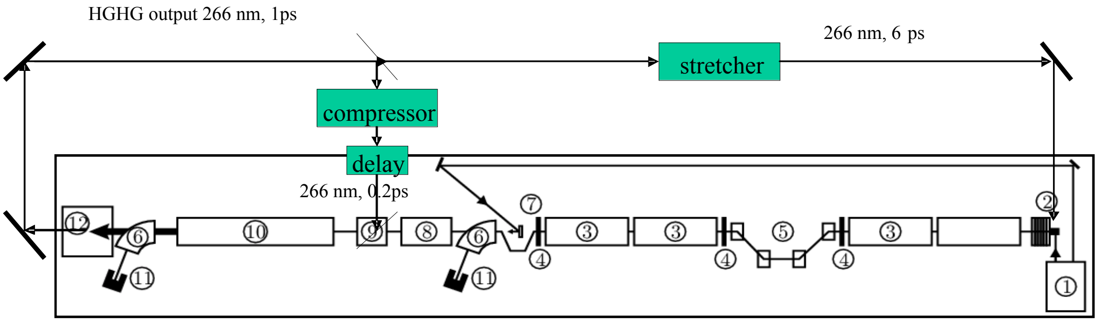

Figure 12: Regenerative synchronization of a seed pulse and electron bunches [ref].

power as a function of the relative delay between the seed and the electron bunch can be used to characterize the electron beam parameters as a function of time within the electron bunch length. This information is very important for the understanding of the properties of the electron beam.

However, there is a time jitter of about 300 fs FWHM, as we have mentioned before. This will give an error bar about the current profile obtained by the scanning of the short pulse HGHG. Hence a statistical analysis of the measured scanning data should be carried out to compare with theory to see if this error bar profile is consistent with the 300 fs jitter, measured by the electro-optical method.

This experiment does not need new hardware, and has already been in an early stage of study. The success of this experiment will confirm the feasibility of the proposed cascaded HGHG experiment. In particular, it will confirm the theoretical prediction of the relation between the output pulse energy fluctuation and the time jitter.

Regenerative synchronization of a seed laser with the electron bunch

As we mentioned before, it is important that the time jitter between the seed laser pulse and the electron bunch should be much smaller than the electron bunch length. This condition is roughly satisfied in our proposed cascaded HGHG experiment: the jitter is 300 fs FWHM while the electron bunch is 1ps. However, further reduction of this jitter is desirable: it will reduce the fluctuation caused by the time jitter. Furthermore, in the future possible multi-staged cascaded HGHG FEL, we may need to use more than two “fresh” parts of the electron bunch, and to achieve much shorter wavelength, we may need higher current so the electron bunch should be further compressed, thus the electron bunch length may be shorter (e.g., 400 fs bunch length for a 750 A current with the same electron bunch charge of 300 pC for our case to achieve 2 nm soft-x-ray FEL). Both of these will require the time jitter to be further reduced.

Our recent analysis provides a new scheme to reduce the time jitter from 300 fs to below 50 fs [17]. In this scheme, as shown in Figure 12, the HGHG output at 266 nm is sent back to the photo-cathode of the RF gun to generate a second electron bunch. In the mean time, a beam splitter will divert a small fraction of the HGHG output to seed the next HGHG stage. In the specific example as described in detail in the reference [17], using the present DUVFEL as a demonstration of the basic principle of this regenerative synchronization scheme, the 1 ps output of the HGHG pulse will be stretched by a pulse stacking method to the desired photo-cathode pulse length of 8 ps, while the split seed pulse for the next HGHG stage is compressed to 200 fs or less. The first cathode drive laser pulse may have a time jitter relative to the RF phase of the order of 300 fs, however, since the first seed pulse is a few ps long, and the electron bunch is 1ps long, the jitter will not cause any significant fluctuation in the first HGHG output.

Since the first HGHG output pulse length is completely determined by the 1ps electron bunch length, it is exactly synchronized with the electron bunch. The electron bunch at the exit of the RF gun has a time jitter of about 300 fs, i.e., the same as the time jitter of the photo-cathode laser, which is exactly synchronized with the seed laser pulse. However, since the electron bunch is compressed from 6 ps to 1 ps, the time jitter of the electron bunch after the compressor is also reduced by the compression ratio of 6, i.e., reduced from 300 fs to 50 fs. Hence, the jitter of the HGHG output is also reduced to 50 fs relative to the RF system. Thus the second electron bunch at the exit of the RF gun jitters also less than 50 fs.

Much more detailed and lengthy analysis as given by reference [17] shows that the time jitter between the second seed pulse and the second electron bunch is reduced by the compression ratio when compared with the jitter between the first electron bunch and the external laser, i.e., it is reduced from 300 fs to 50 fs. As a by-product, the electron beam energy fluctuation of the second electron bunch is also reduced by the same compression ratio, which in our DUVFEL case is about 5 to 6. Due to the high stability of HGHG process, the operation condition of HGHG can be arranged to fully explore the slow varying nature of the peak of the Bessel function in the micro-bunching process [18] so that if the seed intensity is higher then the output of HGHG will be slightly lower and vise versa. Like negative feedback, this further reduces the intensity fluctuation HGHG output.

As we can see from this brief discussion and as described in detail in reference [17], the required hardware for this synchronization experiment mainly consists of an optical transport line, an optical compressor, and a pulse stretcher, all the rest is the existing DUVFEL system. Hence the cost is also very low.

Once this synchronization is achieved, a detailed study of the temporal structure of the electron bunch in the time resolution of about 50 fs can be realized, and a much more stable output in the cascaded HGHG output can be expected, making it much easier to generalize the cascaded scheme to more stages and reach much shorter wavelength. This would be a significant advance in the field.

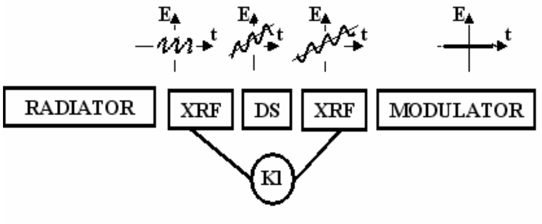

Figure 13: Scheme to tune the HGHG output wavelength without changing the seed wavelength [19]

Tunable HGHG without changing seed wavelength

A new practical scheme to tune the HGHG output wavelength without changing the seed wavelength has been proposed recently [19]. The scheme uses the fact that the dispersion section slightly compresses the electron bunch if it is energy chirped. As shown in Figure 13, after passing the modulator the electron bunch is chirped by a first RF cavity ("XRF"), and then, after passing through the dispersion section "DS" the chirp is removed by the second RF cavity. The energy modulation impressed upon the electron beam in the modulator is converted into micro-bunching in the dispersion section as in the usual HGHG process. However, the electron bunch is slightly compressed too, resulting also the slight compression of wavelength (if the chirp is positive, i.e., the tail of the bunch has higher energy). If the chirp is negative, it is obvious that the wavelength will become longer.

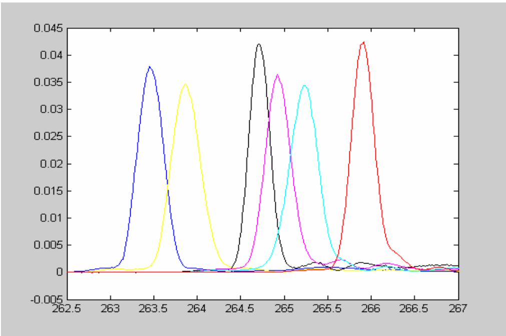

Figure 14: The spectrum of several HGHG output with different chirp but for a fixed seed wavelength.

Recent experiment at DUVFEL has used the chirp generated in the last section of the accelerator to confirm a 1% tuning. The spectrum of several HGHG output with different chirp but for a fixed seed wavelength are shown in Figure 14. With increased dispersion section we can verify larger tuning range. An analysis shows that it is possible to tune 20% wavelength when the two RF cavities shown in Figure 14 are used. It is obvious that this will greatly simplify the tuning of the HGHG process, and will have wide applications.

Summary

Based on the previous analysis, and the impact and scale of the several experiments, we can summarize these experiments in the order of a suggest time sequence as follows:

- Chirped Pulse Amplification
- HGHG with seed shorter than electron bunch length
- 8th harmonic HGHG (800nm→100nm)
- Regenerative synchronization of seed pulse and electron bunch
- Tuning of HGHG without changing seed
- Cascading using NISUS + VISA: 400nm →100nm→50nm.

It is seen that the cascading experiment requires the removal of the last 4 meters of NISUS and the installation of the VISA section, which will be a significant interruption of the DUVFEL schedule. Also the assembly and measurement of the VISA system will take time. Therefore, even though the cascading will have the most important impact, it is suggested to be implemented after the completion of the first five experiments. We emphasize that, as we have explained, this cascading experiment design is based on the existing beam parameters and existing parts, the experiment is not only very important, it is also rather realistic and cost effective.

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