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Accurate synchronization between short laser pulse and electron bunch by using HGHG output at 266 nm as photo-cathode laser for RF-gun

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Synchronization between seed laser pulse and electron bunch to bellow 50 fs is a critically important issue in carrying out cascading HGHG stages to achieve intense temporally coherent x-ray FEL. The single stage HGHG experiment in the IR and recently in UV region has achieved significant success. Hence the next step, to demonstrate the cascading of 2 stages of HGHG becomes crucially important in confirming the viability of this scheme.

Based on our experiences at DUVFEL during the HGHG experiment, we can measure the time jitter between the electron bunch and the RF phase before compression to a high precision of order of 50 fs. Without the compression, this is equal to the time jitter between the laser and the RF phase. An analysis of this measurement suggests that it is possible to use a fast feedback system to reduce the jitter significantly. However, during the successful HGHG experiment at 266 nm recently, we realized that there is a simpler way to achieve highly accurate synchronization. Here we describe the method.

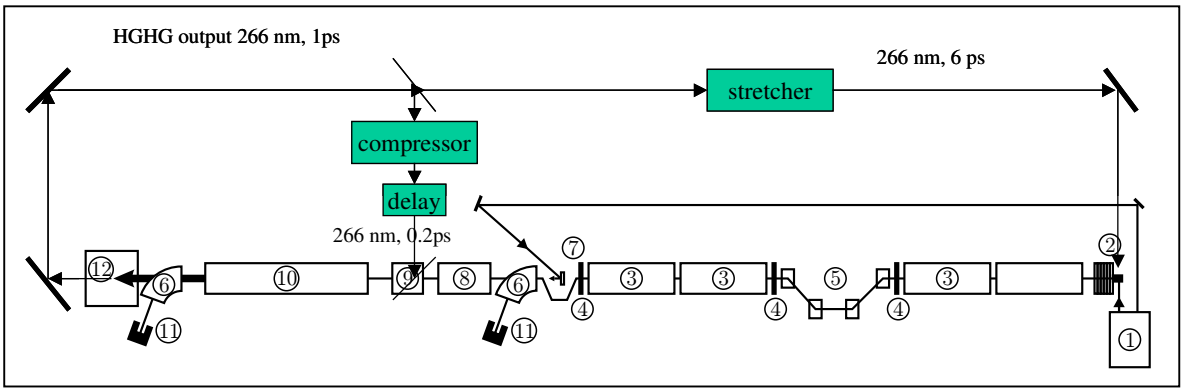

Figure 1. The NSLS DUVFEL layout: 1 – gun and seed laser system, 2 – RF gun, 3 – linac tanks, 4 – focusing triplets, 5 – magnetic chicane, 6 – spectrometers dipoles, 7 – seed laser mirror, 8 – modulator, 9 – dispersive section, 10 – radiator (NISUS), 11 –beam dumps, 12 – FEL radiation measurements area.

During the HGHG experiment, we obtained consistently more than 100 μJ output at 266 nm. The output is very stable, with 7% rms fluctuation. The seed pulse at 800 nm is about 3 to 4 ps long, and the electron pulse is 1 ps long. It is clear the time jitter of the seed of the order of 0.5 ps to 1ps does not affect the HGHG output. However, the output of HGHG has about the same pulse length as the electron bunch length when the HGHG process is deep saturated, as our experiment show. Therefore the HGHG output is perfectly synchronized with the electron bunch.

Now the idea of accurate synchronization is to split this HGHG output into two beams as shown in Figure 1, send 90% of the intensity back to the photo-cathode of the RF gun to generate a second electron bunch, and use the rest of the 10% as a seed for the second electron bunch with appropriate delay. The crucially important point is now that both the new seed and the electron bunch are highly accurately synchronized with the RF phase, as we shall explain now.

The time interval between the Ti-Saphire photo-cathode laser pulse reaching the cathode and the HGHG pulse reaching the cathode again is about 300 ns, corresponding to the round trip distance from the RF gun to the end of the NISUS undulator exit, about 100 m. During this 300 ns, the phase and amplitude of the RF system do change, but the change is a systematic change determined by the RC circuits in the modulator of the RF system. The ringing of the system seems to be random but actually is reproducible from shot to shot. Now, because the new seed laser and the cathode laser beam are perfectly synchronized with the first electron bunch, after 300 ns they still have the same fixed phase relation with the RF phase even though the RF phase fluctuate relative to the Ti-Saphire laser from shot to shot.

The macro pulse of the RF is more than 1 μs, usually we operate the cathode laser pulse at the peak of this pulse which is near the end of a nearly flat top. For our case, we shall send the first Ti-Saphire laser pulse about 300 ns earlier, so that the second pulse will arrive at the cathode at the peak to optimize the second electron bunch for use in cascading HGHG to x-ray. Shortly after the second electron bunch, the RF power will drop, so there is no third electron bunch with similar quality.

The time jitter between the first electron bunch and the RF phase is reduced by the compression process. For example, if the time jitter between the Ti-Saphire laser and the RF phase is 0. 6 rms, and in the electron beam compressor the 6 ps electron bunch at the cathode is compressed to 1 ps pulse after the chicane, then the time jitter of the electron bunch relative to RF phase is reduced to 0.1ps rms. Since the HGHG output is perfectly synchronized with the first electron pulse, its jitter relative to RF is also 0.1ps rms. Because the 300 ns delay only changes the phase relation reproducibly from shot to shot, the second cathode laser and the second seed laser from the HGHG process also jitter about 0.1ps rms only.

To have the RF gun operating correctly, we need to stretch the 1ps HGHG pulse to about 6 ps, hence in Figure 1 we show a stretcher after the beam splitter. On the other hand, to carry out a cascading experiment using the “fresh bunch technique”, we need to use a

seed pulse much shorter than the electron pulse. Hence we show a compressor. In this example of a proof-of-principle experiment, we compress the seed pulse to 0.2 ps. Also shown in the figure is a delay line for the seed laser because we need to arrange the new seed and the second electron bunch to arrive at the NISUS at the same time. To accomplish this compression, we need to operate the HGHG in a chirped pulse amplification (CPA) mode. The CPA mode operation is being planned at the DUVFEL to be carried out in near future. Analysis showed that with the present 1% bandwidth of the T-Saphire laser it is possible to compress to about 50fs.

The optical path length of the second cathode laser can be arranged so that it will reach the cathode at about the same RF phase as the first electron bunch. Again, this is because even though the RF phase changes during the 300 ns period, but the change is highly reproducible.

The loss in the stretcher at 266 nm is of order of 75%, hence the second cathode laser pulse energy is about 25 μJ, if we use the present HGHG output number of 100 μJ as the input to the stretcher. This is lower than what we need for the copper cathode now: about 60 μJ. There are two solutions to the problems. One is to use the magnesium cathode to increase the cathode photo efficiency. The other is to improve the HGHG output. Actually, so far the maximum output of the HGHG experiment is 200 μJ when the 800 nm seed is optimally maintained. We expect the HGHG output will reach steady output of more than 200 μJ in near future.

The new seed and the second electron bunch are accurately synchronized. Hence the 266 nm FEL amplifier using them can be used to study the FEL performance as has never been done before: we can move the seed to different parts of the second electron bunch and measure the gain for different slice of the bunch. Since the second electron bunch has a very small jitter relative to the RF gun, its performance will be very stable, and can be used to optimize the electron gun operating conditions.

As a first step to test this idea, we do not need the stretcher and the compressor at the first stage of the experiment. We only need an optical transport line for the HGHG output to be sent back to the cathode. The second electron bunch will reach the detector 11 at the end of the NISUS after passing through the energy spectrometer 6, as the first electron bunch, and observed together with the first electron bunch. Since the first electron bunch has been used by the HGHG process, it has large energy spread, while the second one will have small energy spread. So it is easy to distinguish them.

Since the second electron bunch has much smaller time jitter than the first one we should see much smaller energy fluctuation compare with the first one. This will be a proof of the success of this scheme.

What we discussed here is the first proof-of-principle experiment for thi high accuracy synchronization method. With higher compression ratio to 10 and improvement of the time jitter between Ti-Saphire laser and RF to bellow 0.5 ps (an improvement work is

under way to largely reduce this jitter at the DUVFEL now) the residual jitter can be reduced to bellow 50 fs.

Since the second electron pulse is separated from the first by 300 ns, there are many ways to separate them in the future plan. For example, the magnetic kicker with speed faster than a few tens of ns used in storage rings can be used for this purpose.

The other possible residual jitter may come from the vibration of the mirrors in the long distance transport of the HGHG output to the cathode. However, since most vibration on the floor is order of sub microns, it will contribute to the jitter by only about a few fs at the most.

As it is seen here, the scheme is rather simple and straightforward, and can be carried out in the near future. Once this is confirmed, the next natural step would be a demonstration of cascading HGHG experiment at the DUVFEL.