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RECENT FEL EXPERIMENTS AT FLASH

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Abstract

The FLASH free-electron laser user facility at DESY (Hamburg, Germany) provides high brilliance SASE FEL radiation in the XUV and soft X-ray wavelength range. With the recent installation of a second undulator beamline (FLASH2), variable gap undulators are now available. They now allow various experiments not possible with the FLASH1 fixed gap undulators. We report on experiments on tapering, harmonic lasing, reverse tapering, frequency doubling at FLASH2 and experiments using double pulses for specific SASE and THz experiments at FLASH1.

INTRODUCTION

Since summer 2005, FLASH, the free-electron laser (FEL) user facility at DESY (Hamburg), delivers high brilliance XUV and soft X-ray FEL radiation for photon experiments [1, 2]. In 2013/14, the facility has been upgraded with a second undulator beamline (FLASH2), being the first FEL facility worldwide operating simultaneously two undulator lines [3,4]. The FLASH2 beamline is equipped with modern variable gap undulators allowing now a variety of FEL experiments which have not been possible before. The 12 planar undulators have a period of 31.4 mm, a length of 2.5 m each with an adjustable $K_{\text{rms}} = 0.7$ to 1.9.

A planar electromagnetic undulator, installed downstream of the FLASH1 SASE undulators, provides THz radiation for user experiments [5,6]. In order to facilitate THz-XUV pump-probe experiments, double pulse lasing has been developed to provide SASE and/or THz pulses with a variable and shorter delay in the nanosecond scale than the usual 1 µs.

More details of the FLASH facility are described in [3, 4, 7, 8] and references therein. An overview on photon science at FLASH can be found in the publication list of [9].

The amplification process in a free-electron laser (FEL) can be effectively controlled by means of changing its resonance properties along a gap tunable undulator with integrated phase shifters. Novel schemes for the generation of FEL radiation with improved properties based on the use of variable gap undulators have been developed at DESY and demonstrated at FLASH2. In particular, we report on the first operation of the Harmonic Lasing Self-Seeded (HLSS) FEL [10–13] that allows to improve longitudinal coherence and spectral power of a SASE FEL. We were able to successfully demonstrate the validity of the reverse tapering concept [14–16] that can be used to produce circularly polarized radiation from a dedicated afterburner with strongly suppressed linearly polarized radiation from the main undulator. This scheme can also be used for an efficient background-free production of harmonics in an afterburner. We performed experiments on the frequency doubling scheme [17, 18] and were able to extend the photon energy range of FLASH down to Nitrogen K-edge (400 eV), far below original design parameters. The described FEL schemes can easily be implemented at large scale X-ray FEL facilities [19–22], and the scientific community will definitely benefit from these innovative extensions.

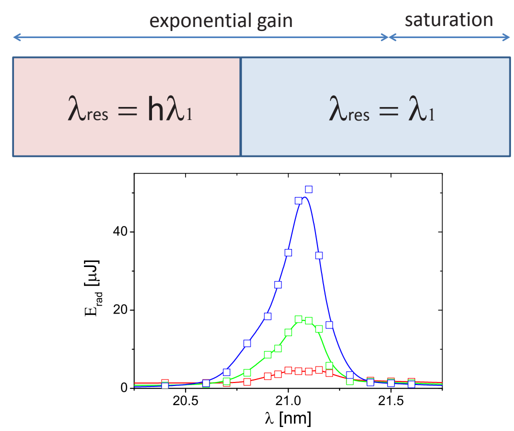

Figure 1: Top: conceptual scheme of a harmonic lasing self-seeded FEL. Bottom: operation of HLSS at FLASH2. Scan of the resonance wavelength of the first part of the undulator consisting of one undulator section (red), two sections (green), and three sections (blue). Pulse energy is measured after the second part of the undulator tuned to 7 nm.

HARMONIC LASING SELF-SEEDED FEL

In addition to well-known seeding and self-seeding techniques with enhanced spectral brightness [23–25], there are schemes without using optical elements. One of them is based on the combined lasing on a harmonic in the first part of the undulator with increased undulator parameter K, and on the fundamental in the second part [11]. In this way the second part of the undulator is seeded by a narrow-band signal generated via harmonic lasing in the first part (top plot in Fig. 1). This concept was named HLSS FEL (Harmonic Lasing Self-Seeded FEL). The enhancement factor of the coherence length (or, bandwidth reduction factor), that one obtains in an HLSS FEL in comparison with a reference case of lasing in SASE FEL mode in the whole undulator, is $R \simeq h[L_{\text{w}}^{(1)} L_{\text{sat},h}]^{1/2}/L_{\text{sat},1}$ [11]. Here h is harmonic number, $L_{\text{sat},1}$ is the saturation length in the reference case of the fundamental lasing with the lower K-value, $L_{\text{w}}^{(1)}$ is the length of the first part of the undulator, and $L_{\text{sat},h}$ is the saturation length of harmonic lasing. Despite that the bandwidth reduction factor is significantly smaller than of traditional self-seeding schemes [23–25], the HLSS FEL scheme is very simple and robust, and it does not require any addi-

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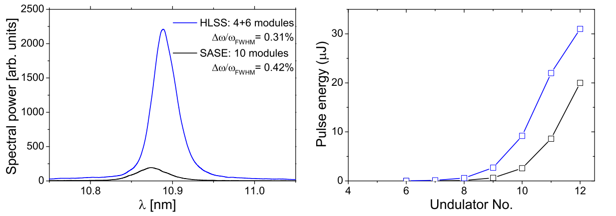

Figure 2: Comparison of SASE FEL and HLSS FEL operation at FLASH2. Left: Spectral density of the radiation energy for HLSS FEL configuration (blue) and for SASE FEL (black). Right: Radiation pulse energy versus position in the undulator for HLSS (blue) and for SASE (black) at 15 nm. Post-saturation taper was optimized for both cases.

tional installations. It can always be used in gap-tunable undulators with a sufficiently large K-value range.

On May 1, 2016 we demonstrated the first operation of HLSS FEL at FLASH2. Initially we tuned 10 undulator sections to standard SASE, operating in the exponential gain regime at a wavelength of 7 nm ($K_{\mathrm{rms}} = 0.73$); the pulse energy was 12 µJ. Then we detuned the first section and tuned it to the third subharmonic ($K_{\mathrm{rms}} = 1.9$) and scanned it around 21 nm (see Fig. 1). We repeated the measurements with the first two sections, and then with the first three sections. The fundamental at 21 nm was in the exponential gain regime with a pulse energy of 40 nJ after three undulator sections, far away from the saturation level of 200 µJ. This means that nonlinear harmonic generation in the first part of the undulator is excluded. It is seen from Fig. 1 that the effect is essentially resonant. The ratio of pulse energies at the optimal tune (21.1 nm) and at the tune of 20 nm away from the resonance is equal to 170.

In the following runs at different wavelengths (between 4.5 nm and 15 nm) we were able to demonstrate an improvement of the longitudinal coherence and brilliance of HLSS with respect to SASE, and also a better performance using post-saturation tapering (see Fig. 2). Both configurations use the same electron beam and the same undulator length. The left plot in Fig. 2 shows the averaged spectra for two study cases: SASE FEL with ten undulator modules, and HLSS FEL with four modules tuned to 33 nm plus six modules tuned to 11 nm. The spectral powers differ by a factor of six due to an increase of the pulse energy in the HLSS regime by a factor of five, and of the bandwidth reduction by a factor of 1.3 (0.31% for HLSS versus 0.41% for SASE). Note that the spectral width has been visibly widened due to an energy chirp along the electron beam. The coherence time has been improved by a factor 1.8 with respect to SASE. As a result, undulator tapering works more effectively in the case of HLSS FEL due to the improved longitudinal coherence (right plot in Fig. 2).

REVERSE UNDULATOR TAPER

Most X-ray FEL facilities are equipped with planar undulators generating linearly polarized radiation. Circularly polarized radiation is generated in a short helical afterburner installed after the main undulator. To obtain a high degree of circular polarization, one needs to suppress the powerful linearly polarized radiation from the main undulator. The most effective suppression technique is reverse tapering of the main undulator [14–16] (see Fig. 3). At optimum taper strength, the bunching factor at saturation is practically the same as in a non-tapered undulator. The saturation length increases only moderately while the saturation power in the reverse tapered case is suppressed by orders of magnitude. The strongly modulated electron beam now radiates at full power in the afterburner.

The reverse tapering scheme has been successfully tested at FLASH2. The radiation energy from the afterburner sections exhibit a clear resonance behavior, and reaches its maximum value when the resonance frequency of the afterburner matches the frequency of the electron beam modulation in the main undulator (see Fig. 3).

An important figure of merit of the afterburner scheme is contrast, the ratio of the radiation power from the afterburner and from the main undulator. We could demonstrate in this experiment that a contrast of 200 is achievable for planar undulators.

In the case of helical afterburners, the contrast will increase up to 400. This means that the degree of circular polarization from a helical afterburner is expected to reach the value of 99.8%.

The density modulation of the electron beam driving a SASE FEL in saturation and in the post-saturation regime

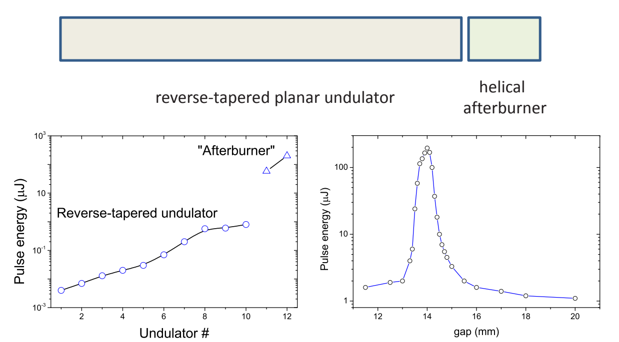

Figure 3: Top: Conceptual scheme to obtain circular polarization at X-ray FELs. Bottom: operation of the reverse tapering scheme at FLASH2. Left: FEL pulse energy versus undulator number. The first ten undulators are reverse-tapered, the last two sections are tuned to resonance to the incoming microbunched beam. Right: gap scan of the afterburner (last two undulator sections). For a completely open gap the pulse energy is below 1 µJ.

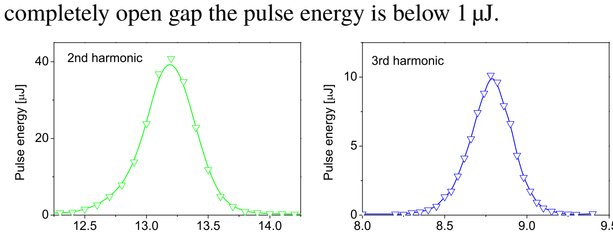

Figure 4: Generation of harmonics in the reverse tapering scheme at FLASH2: radiation pulse energy of the 2^{nd} and the 3^{rd} harmonics versus the resonance wavelength of the afterburner.

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contains a rich spectrum of higher harmonics. The radiation of a SASE FEL with a planar undulator contains higher odd harmonics as well. However, their intensity is pretty low, the 3rd harmonic intensity is in the one per cent level, and the 5th harmonic is on a level of a fraction of a per mille of the fundamental. This is because of debunching of the electron beam at higher harmonics due to the strong interaction of the electron beam with the fundamental harmonic. Another important problem is a strong background of the radiation from the main undulator.

An important feature of reverse tapering in the main undulator is to reach high values of the beam bunching at higher harmonics with very low radiation background from the main undulator. The afterburner tuned to higher harmonics is capable of generating much higher radiation energies than in the untapered case. Relevant experimental results from FLASH2 are presented in Fig. 4. Ten undulator sections (main undulator) have been tuned to the radiation wavelength of 26.5 nm with a reverse undulator tapering of 5%. The two remaining undulator sections have been tuned to the maximums of the power around the fundamental, the 2nd, and the 3rd harmonics. Radiation pulse energies of 150 µJ at the fundamental, 40 µJ at the 2nd, and 10 µJ at the 3rd harmonics have been obtained. We note that the pulse energy of the 2nd harmonic is comparable with the pulse energy of the fundamental, and the pulse energy of the 3rd harmonic exceeds by an order of magnitude the level of the 3rd harmonic from a SASE FEL.

FREQUENCY DOUBLER

In this section we discuss the generation of second harmonic allowing 2-color lasing simultaneously (ω and 2ω) as well as operation at shorter wavelengths [17, 18]. The frequency doubler scheme is conceptually simple (Fig. 5). The first part of the undulator is tuned to the frequency ω. In this part, the amplification process develops up to the onset of saturation when notable beam modulation at the fundamental and higher harmonics occurs, but the radiation power does not reach saturation yet. Then the modulated electron beam enters the second part of the undulator tuned to the frequency 2ω. Now the beam modulation corresponding to the 2nd harmonic seeds the amplification process.

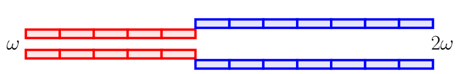

Figure 5: Conceptual scheme of a frequency doubler.

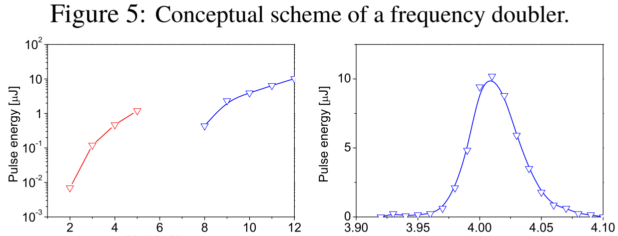

Figure 6: Left: gain curve of the frequency doubler at FLASH2. The first part of the undulator (5 modules) is tuned to 8 nm, the second part (7 modules) to 4 nm. Red and blue colors correspond to the radiation wavelength of 8 nm and 4 nm, respectively. Right: radiation pulse energy of the 2nd harmonic versus the resonance wavelength of the second part of the undulator.

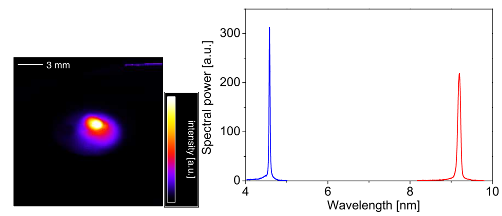

Figure 7: Photon beam image in the experimental hall (left) and radiation spectra (right) of the frequency doubler at FLASH2 showing 2-color lasing. The small yellow spot is 4.5 nm (2nd harmonic) radiation, the pulse energy is 10 µJ. The larger blue/pink spot is 9 nm radiation with a pulse energy of 10 µJ. The electron beam energy is 1080 MeV, the bunch charge 300 pC.

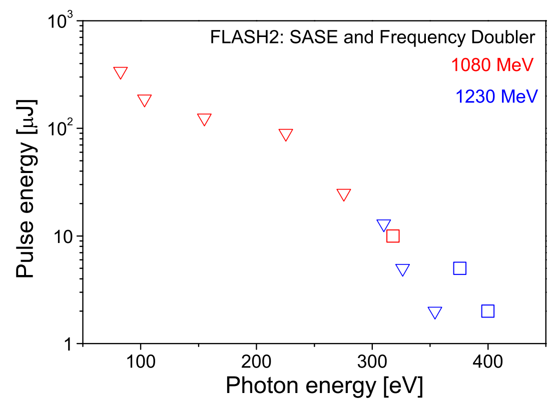

Figure 8: Radiation pulse energy of SASE (triangles) and frequency doubler (squares) obtained for various photon energies. The data are plotted for an electron beam energy of 1080 MeV and 1230 MeV resp.

The operation of a frequency doubler has been successfully demonstrated at FLASH2. Figure 6 shows the gain curve of a frequency doubler 8 nm *to* 4 nm. The first five undulator sections are tuned to 8 nm, and the last seven sections to 4 nm. Scanning the gap and thus the wavelength of the second part exhibits a clear resonance behavior in the amplification process at the 2nd harmonic frequency (right plot in Fig. 6). This result clearly shows, that the beam bunching at the second harmonic seeds the amplification process of the frequency doubling section. Note, that seeding with the 2nd harmonic of SASE is excluded, since even harmonics are strongly suppressed in planar undulators.

The tuning procedure of the frequency doubler is simple and reproducible. In particular, it is possible to tune the relative energies of two colors ω and 2ω in a wide range. When tuned to equal pulse energies, a few to ten microjoules are obtained. Figure 7 shows a photon beam image and spectra as an example for 2-color lasing at FLASH2. With this first experience we can state that this operational mode can be proposed to users.

The frequency doubler scheme is also capable to generate shorter wavelength radiation than standard SASE. The first

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part of the undulator operates at twice the wavelength, and saturation is obtained at half of the full undulator length. The induced beam bunching at the second harmonic is much larger than the shot noise in the electron beam, and it becomes possible to reach saturation on a much shorter length of the doubling section.

We performed two dedicated runs at FLASH2 with electron energies close to the limit of the accelerator. Both, SASE and the frequency doubler are optimized for maximum radiation pulse energy with the same electron beam. The results of pulse energy measurements are compiled in Fig. 8. We could reach shorter wavelengths with the frequency doubler, down to a record of 3.1 nm (400 eV) demonstrating photon energies above the Nitrogen K-edge. This significantly exceeds the original specification of the lowest wavelength of 4 nm for FLASH2.

DOUBLE PULSE OPERATION

FLASH is an accelerator based on superconducting technology which allows the acceleration of many bunches in a so-called burst with a length of up to 800 µs (10 Hz repetition rate). FLASH uses a laser driven photo-injector to generate high brilliance electron bunches. The distance of the bunches in a burst is given by the present laser design to 1 µs; a few longer distances are possible as well (2, 4, 5, 10, 20, and 25 µs).

A variety of experiments would profit from an operation mode with two bunches closer than the usual bunch distance of 1 µs. The split & delay method allows to generate very closely spaced double bunches of a few picoseconds up to a few tenth of nanoseconds. The split & delay method becomes unpractical for larger distances. To extend the double pulse spacing for large distances, two laser systems are used simultaneously.

Double Pulses with Close Spacing

A unique feature of FLASH is a planar electromagnetic undulator installed downstream of the FLASH1 SASE undulators [5]. It provides THz radiation for user experiments in the wavelength range from a few micrometers to 200 µm (300 THz to 1.5 THz). An important feature is the precise synchronization of the THz pulses with the XUV and soft-X ray pulses, since both are produced by the same electron beam. Together with an optical laser, this arrangement allows THz-XUV-optical pump-probe experiments.

However, due to the specific THz beamline design [6], the THz pulses arrive much later (about 20 ns) at the experimental station than the XUV-pulses. A solution is to let the XUV-pulses propagate over the interaction point by 10 ns and back-reflect the radiation by special coated high-reflective mirrors. The disadvantage of this scheme is, due to the usually very small bandwidth of the mirror coating, that only one single XUV-wavelength can be used.

An elegant solution with the advantage that the XUV-wavelength is not fixed by the XUV-mirror is the use of double pulses with an appropriate distance to cancel the THz/XUV path difference. In this scheme, the first electron bunch is tuned to provide a good THz radiation pump-pulse, and at the same time the second pulse is optimized for SASE radiation providing the XUV-probe pulse. Figure 9 shows the principle idea of this method.

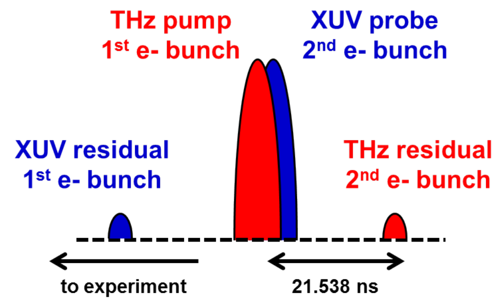

Figure 9: Principle of the THz-Doubler. Two electron bunches are generated with a delay of 21.538 ns (28 RF-buckets). The first one generates a good THz-pump pulse (red) while SASE is suppressed. The second one generates a good XUV-probe SASE pulse (blue) while THz is suppressed. The THz-pump and XUV-probe pulses are overlapping in the experiment.

The distance of the pulses must fit into an integer multiple of an 1.3 GHz RF-bucket, the frequency of the accelerator. One RF-bucket corresponds to 769.2 ns, 28 RF-buckets corresponds to 21.538 ns. The doubler electron pulses are generated with a split & delay unit at one of the three photo-injector laser (laser 1). The split & delay unit is a copy of the one already built in 2006 for a similar purpose [26]. Note, that with this arrangement, the complete burst of up to 800 pulses is automatically doubled.

Three laser knobs are available for tuning the two pulses independently: the phase in respect to the RF, pulse energy, and position on the cathode. All other parameters, especially the accelerating amplitude and phase of the accelerator cannot change within the 21 ns. The phase of pulse 1 is set with the phase of an 1.3 GHz RF-signal used to synchronize the laser oscillator. The phase pulse 2 is adjusted with a remote controlled delay stage in the delayed arm of the split & delay unit. The laser pulse energy is adjusted with variable attenuators realized with a remote controlled half wave plate together with a polarizer independent for both pulses allowing different bunch charges for pulse 1 and 2. To slightly correct the orbit in the accelerator, the position of both pulses on the cathode is slightly corrected remotely. The THz-doubler is permanently installed in the laser beamline [27], pulse 2 is switched in by simply opening a shutter.

First experiments with the THz-doubler have been performed to set-up THz and XUV-radiation for both pulses and to suppress XUV for the first and THz for the second. Some pump-probe experiments may not accept THz and XUV for both pulses.

Since the THz radiation is generated by the same electron bunch than the corresponding XUV signal, both are inherently synchronized to the few femtosecond level ($< 5\ fs$). The question is, whether this is also the case for pulse 1 and

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2? Since the split & delay unit is built with fixed mirrors, and acceleration parameters in a distance of 20 ns should be the same, we expect a similar stability. A measurement using spectral decoding has been set-up to determine the arrival time jitter between pulse 1 and 2. Preliminary results show a jitter of less than 50 fs limited by the resolution of the set-up [28]. Next steps are an improvement of the experiment and a construction of an experimental set-up using the new double pulse scheme..

For completeness, we would like to mention that a similar split & delay unit is used by the FLASHforward experiment [29]. It is installed in the second laser system and provides a very short delay of the second pulse by a few picoseconds only for plasma acceleration experiments in the third beamline of FLASH.

Double Pulses With Large Spacing

On the request of a user experiment (AG Chapman) a new scheme has recently been developed to generate XUV double-pulses with an arbitrary variable delay.

The FLASH photoinjector has three drive lasers to produce electron bunches. All three lasers can be sent simultaneously in any beamline [27]. Usually one laser serves FLASH1, the second one the FLASH2 beamline.

In the new double pulse scheme, two lasers are sent simultaneously into one FLASH beamline while the third laser is used for the second beamline. The lasers are delayed in respect to each other to the requested distance.

In order to have equal beams for both pulses, it is important that the double pulse distance is an integer multiple of an RF-bucket of the accelerator. Even though arbitrary delays can be realized, for the sake of easy use, the user interface allows to set the delay in steps of 9.2 ns (the FLASH beam diagnostics use 108 MHz ADC boards). Once set-up, the delay can be changed at any time. At every delay step, the laser is kept exactly at the same phase in respect to the RF of the accelerator within 100 fs. This is guaranteed by active mode-locking of the laser oscillator to the 1.3 GHz RF-frequency of the accelerator.

In order to achieve the same XUV-radiation properties for both pulses, still a few adjustments have to be done. Tuning knobs are similar to the THz-doubler: the laser energy, laser phase, and position on the cathode. A slight tuning of the orbit, and a slight change in compression is required as well. Note, that in contrast to the small delay of the THz-doubler, large delays may exhibit slightly different amplitude and phase of the accelerating structures which need to be corrected.

The specific user experiment set-up at FLASH1 used a delay of 221.5 ns and 470 ns respectively to study the recovery time of a liquid jet hit by a XUV pulse [30]. The experiment has been performed with a SASE wavelength of 4.29 nm. The first pulse was tuned to an energy of 18 µJ, the second pulse to 10 µJ running stable for the duration of the experiment of several hours. Figure 10 shows an example of a liquid jet hit by the double pulses. Pulse 1 disrupts the flow of the liquid. When pulse 2 arrives with a delay of 221.5 ns, the jet has already recovered. This shows, that experiments with liquid jets are feasible for high repetition rate beams as the European XFEL provides.

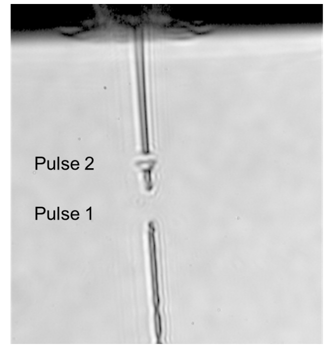

Figure 10: Example of a liquid jet hit by the double XUV-pulses (4.29 nm). Pulse 1 disrupts the flow of the liquid. When pulse 2 arrives with a delay of 221.5 ns, the jet has already recovered. Courtesy Max Wiedorn, CFEL, Hamburg, Germany.

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