Flexible and Coherent Soft X-ray Pulses at High Repetition Rate: Current Research and Perspectives

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Abstract: The successful realization of high gain free-electron lasers has opened new possibilities to X-ray scientists for investigating matter in different states. The availability of unprecedented photon properties stimulated the development of new experimental techniques capable of taking full advantage of these options and has started a virtuous collaboration between machine experts and photon users to improve further and optimize the generated X-ray pulses. Over the recent years, this has led to the development of several advanced free-electron laser (FEL) schemes to tailor the photon properties to specific experimental demands. Presently, tunable wavelength X-ray pulses with extremely high brilliance and short pulse characteristics are a few of the many options available at FELs. Few facilities can offer options such as narrowband or extremely short pulses below one fs duration and simultaneous pulses of multiple colors enabling resonant X-ray pump—X-ray probe experiments with sub fs resolution. Fully coherent X-ray radiation (both spatial and temporal) can also be provided. This new option has stimulated the application of coherent control techniques to the X-ray world, allowing for experiments with few attoseconds resolution. FELs often operate at a relatively low repetition rate, typically on the order of tens of Hz. At FLASH and the European XFEL, however, the superconducting accelerators allow generating thousands of pulses per second. With the implementation of a new seeded FEL line and with an upgrade at FLASH linac, all the new features will become available in the soft X-ray spectral range down to the oxygen K edge with unprecedented average photon flux due to the high repetition rate of pulses.

Keywords: free-electron laser; X-ray; seeding; harmonic generation

1. Introduction

The advent of high gain single-pass free-electron lasers (FEL) [1–3] and the subsequent development of FEL user facilities [4–10] have led the scientific progress in many fields making completely new options available to scientists. Using the unique capabilities of FELs, light pulses with extremely high brightness and short time duration can be produced over the spectral range going from the VUV down to the hard X-ray range and are often combined with secondary sources with longer wavelengths across the visible, infrared, and THz domains.
Since the first FEL pulses became available to users at FLASH (DESY Hamburg, Germany) [4] more than 15 years ago, there has been continuous technological and scientific progress allowing to extend the parameter range accessible by these sources. The use of higher energy accelerators combined with high brightness electron beams has allowed exceeding the 25 keV of photon energy [11]. Moreover, the recognizable progress in the undulator design has made features such as variable polarization available [12,13]. The latter, in combination with the accurate control of the beam dynamics, supported advanced options for two-colors or two pulses [14,15] or harmonic lasing [16–18] that have been proposed and delivered to the users.

The control of the coherence of the X-ray pulses has also become attainable due to the seeding techniques relying on external lasers [19–21] or intermediate monochromatization during the FEL process [22–24]. Thanks to the availability of fully coherent sources in the XUV and soft X-ray spectral range, coherent control [25] has recently been extended to the this spectral range opening the door to a new field of research that is growing very fast [26–29]. Coherent control methods developed in the optical regime are now possible at much shorter wavelengths enabling new science by addressing elementally selective core resonances uniquely found at these wavelengths. Full control of the FEL pulse phase has become possible and exploited in a variety of experiments [26,27,29–32].

Each FEL pulse contains a large number of photons but the number of pulses typically produced by FELs is limited to a few tens per second being limited by the repetition rate of the accelerator. This limit is overcome by the use of superconducting accelerating cavities [33] that can allow for much higher repetition rates. Currently, only FLASH [34] and European XFEL [10] are relying on this technology and can produce several thousands of pulses per second. Few more facilities are planning to use the same technology to go even further [35,36]. At present, these high repetition rate FELs only operate in Self Amplified Spontaneous Emission (SASE) [37,38] mode and development toward highly coherent FELs at high repetition rate are still ongoing [39]. Very recently European XFEL has demonstrated the possibility to operate the self-seeding setup in multi-bunch mode showing effects produced by the heat load into the monochromatizing crystal [40] that need to be understood and solved before being able to reach the full accelerator repetition rate. To date, no externally seeded FEL exists that provides more than 50 pulses per second, mainly due to the challenge to develop a laser system that is capable of satisfying the stringent requirements for seeding with the high repetition rate of superconducting accelerators.

The FLASH2020+ upgrade project [41,42] is aiming at covering this empty space by combining an upgrade of the accelerator, an ambitious R&D program for the seed laser [43] and a new undulator setup.

With such an upgrade new scientific avenues are opened in various fields: in general, the higher repetition rate ideally caters to photon-hungry experiments that need to average over many (thousands) shots to accumulate statistically meaningful data. Very often though, such experiments provide an unprecedented information depth making them very interesting for scientists. Examples of such experiments are often found in the field of spectroscopy. For example, photoelectron spectroscopy at FELs is often limited in the ability to accept intense photon pulses due to space-charge effects in the emitted electron cloud. This fundamentally limits the achievable signal levels even with the most advanced spectrometers that accept emission cones of 2\(\pi\) solid angle [44]. Only a high repetition rate machine can then enable complex experiments at a reasonable time. Other experimental techniques that strongly benefit from high repetition rates are spectroscopies where emitted photons are spectrally analyzed (such as resonant inelastic X-ray scattering or X-ray emission spectroscopy) [45–49] with notoriously weak signal yields, especially at soft X-ray and XUV wavelengths even at high photon numbers. These techniques though provide a tremendous amount of information through their element and chemical state selectivity as well as their polarization and orientation sensitivity due to the involved stringent dipole selection rules. Of course, the high repetition rate is also very beneficial when extremely dilute samples or rare events are being studied [50–53]. Here, only the
gathering of a sufficient amount of data in reasonable measurement durations allows gaining a satisfactory signal above background.

Furthermore, a large number of pulses in a short time interval allows for sampling huge, multi-dimensional parameter spaces not only concerning shot-to-shot FEL beam parameters, but also extending to pump-probe laser parameters (e.g., relative delay to the FEL pulse, pulse lengths, wavelengths, intensity, polarization) and other sample parameters (temperature, external fields, positions, orientations, . . . ). Especially the field of spectroscopy benefits from the increased longitudinal coherence, i.e., the smaller energetic bandwidth of the pulses, where pulse parameters can come close to the optimal point in the trade-off between energy and temporal resolution at the Fourier limit. Here, FLASH will be operated in a regime with sufficient temporal resolution to visualize electronic processes while still providing sufficient spectral resolution to selectively study specific chemical elemental resonances as well as the respective chemical shifts.

Fully coherent pulses are also a prerequisite for transferring modern coherent (spectroscopy) techniques from the laser world to the X-ray realm. Here, first steps have been achieved, but it is becoming apparent that higher-order optical constants are even weaker at shorter wavelengths than in the optical regime. Nevertheless, such techniques often provide information that is unavailable to more traditional methods, such as the spatial motion of excitations in transient grating methods [54,55]. Some of those experiments can be performed in a quasi-background-free manner, but full harvesting of results from such novel X-ray methods requires fully coherent beams at high repetition rate in order to bring weak signal levels above noise floors. With the FLASH2020+ upgrades, the facility will be ideally positioned to open up such complex experiments to the scientific community.

In this work, the parameters of the new facility and the expected performance for the new seeded FEL are reported together with a description of the current capabilities at FLASH.

In Section 2, we describe the FLASH facility and report the nominal performance of the two FEL beamlines which are at present in operation along with the planned changes to the accelerator. Section 3 focuses on the new seeding beamline to be implemented with the FLASH2020+ project covering the spectral range between 60 nm and 4 nm. Section 4 is dedicated to the description of the new laser systems specifically designed for FLASH2020+ to meet the stringent requirements of a seeded FEL at the full repetition rate of the FLASH superconducting accelerator.

2. Flash Free-Electron Laser Facility

FLASH is the XUV and soft X-ray free-electron laser (FEL) user facility operated by DESY [4,34]. The facility consists of two undulator beamlines (FLASH1 and FLASH2) and two experimental halls and relies on a superconducting linac driven by a normal conducting electron RF-gun. In addition to user experiments, FLASH supports R&D in accelerator and FEL fields with experimental programs on external seeding with the Xseed experiment [56] and on plasma wake field acceleration with FLASHForward [57]. The unique use of a superconducting linac allows RF flat-tops of up to 0.8 ms running with a repetition rate of 10 Hz enabling the acceleration of several hundreds of bunches at the repetition rate of the injector laser (1 MHz). The bunch train can be divided into two segments separated by approximately 70 µs to simultaneously operate the two FEL lines [34]. A flexible low-level RF system supporting different amplitudes and phases of the RF-pulses between the two segments allows independent tuning of the electron beam parameters. This scheme enables the flexible adjustment of bunch compression adapted to the specific requirements of the experiments in the two beamlines [34]. In addition, charge and bunch spacing can be adjusted to different needs. Currently, the generation of FEL radiation at FLASH is based on the SASE process [37,38]. With fixed gap undulators, FLASH1 photon wavelength is defined by the electron beam energy and can go down to 4.2 nm with the maximum beam energy of 1.25 GeV. FLASH2 uses variable gap undulators for more flexible wavelength tuning of the FEL. Table 1 shows the typical FLASH operating
parameters before the planned upgrades. Note, that these parameters are not all achieved simultaneously, but indicate the overall span of possible SASE parameters.

Table 1. FLASH FEL radiation parameters available as of 2021.

| FEL Parameter                | Units | FLASH1       | FLASH2       |
|------------------------------|-------|--------------|--------------|
| Wavelength                   | nm    | 4.2–51       | 4.0–90       |
| Average single pulse energy  | µJ    | 1–500        | 1–1000       |
| Pulse duration (fwhm)        | fs    | <30–200      | <30–200      |
| Spectral width (fwhm)        | %     | 0.7–2        | 0.5–2        |
| Peak power                   | GW    | 1–5          | 1–5          |
| Photons per pulse            | photons | 10\(^{11}\)–10\(^{14}\) | 10\(^{11}\)–10\(^{14}\) |
| Peak brilliance               | photons/(mm rad\(^2\) mm\(^2\) 0.1% bw) | 10\(^{28}\)–10\(^{31}\) | 10\(^{28}\)–10\(^{31}\) |
| Average brilliance            | photons/(mm rad\(^2\) mm\(^2\) 0.1% bw) | 10\(^{17}\)–10\(^{21}\) | 10\(^{17}\)–10\(^{21}\) |

2.1. Flash Linac

The available photon parameters are based on the extremely high quality electron bunches produced by the FLASH linac whose main parameters are described in Table 2. The FLASH linac is based on superconducting L-band (1.3 GHz) 9-cell cavities originally developed for the TESLA linear collider project [58] and nowadays also used as the backbone of the European XFEL [59]. It is thanks to the high (RF-) duty factor achievable with superconducting technology, that FLASH provides up to 800 µs long RF flat tops and thus is capable of accelerating thousands of electron bunches per second in 10 Hz burst mode. For user experiments, FLASH provides up to 5000 photon pulses per second.

The electron bunches are generated at a normal-conducting 1.6 cell L-band photocathode RF-gun. The cathodes are Cs\(_2\)Te films on a Molybdenum carrier plug and are excited by a laser system capable of providing UV pulses with a duration selectable from 1 ps to 6.5 ps (rms). The nominal bunch charge is in the range 300–400 pC depending on experimental demands, but it can be varied from 20 pC to 1.2 nC to accommodate special requirements. The electron beam energy at the exit of the gun cavity is 5.6 MeV with an uncorrelated slice energy spread of about 3 keV. The use of a solenoid close to the gun cavity allows compensating for the linear emittance blow up and to generate bunches with normalized transverse emittances of typically 1 mm mrad at 1 nC and 0.4–0.6 mm mrad at 400 pC [60].

Table 2. FLASH electron beam nominal parameters at the undulator in 2021.

| Electron Beam Parameter     | Units   | Current Range |
|-----------------------------|---------|---------------|
| Beam energy                 | MeV     | 380–1250      |
| Bunch charge                | nC      | 0.02–1.2      |
| Peak current                | kA      | 0.6–2.5       |
| Slice energy spread         | keV     | 100           |
| Slice norm. emittance       | mm rad  | 0.4–1.2       |
| Bunches per train           |         | 1–500         |
| Bunch spacing               | µs      | 1–25          |
| Repetition rate             | Hz      | 10            |

In standard operation, the first accelerating module brings the beam to 165 MeV with a moderately negative energy chirp required for bunch compression. Immediately upstream, a third-harmonic (3.9 GHz) module decelerates the beam by 19 MeV. The relative phases of both modules are adjusted to minimize non-linearities in the longitudinal phase space and optimize the compression. Electron beam compression is done with two bunch compressors. First compression occurs at 146 MeV on a magnetic D-chicane with varying momentum compaction (R\(_{56} = 122–255\) mm) set to 142 mm and compressing the beam by a factor 4 to 5. Second compression occurs after the next two accelerating modules at 450 MeV, with further optimization of the energy chirp on the two accelerating modules upstream a
6-dipole S-chicane with large momentum compaction flexibility ($R_{S6} = 7\text{–}122\text{ mm}$) set to 75 mm for reaching the final compression of a factor 8 to 10 required for reaching the kA peak current level.

Electron beam matching is critical for the final FEL operation and is done downstream of the first bunch compressor using a FODO channel with screens to measure optical mismatch and the injector emittance.

Two pairs of additional superconducting modules complete the FLASH linac and allow reaching a maximum beam energy of 1.25 GeV. Each pair of modules is driven by a separate RF station allowing a fine tuning of the final energy profile. The FLASH linac is operated from 380 MeV to 1250 MeV depending on the required photon wavelength.

2.2. Upgrade Plans

To expand upon the current capabilities and meet the increasing demands of future user experiments FLASH is undergoing a significant upgrade in the next years. In the first stage, the linac is upgraded with new bunch compressor and modules to allow for a higher beam energy of 1.35 GeV and flexible compression schemes. Additionally, a laser heater will be added upstream of the first bunch compressor to reduce the adverse effects of microbunching. These upgrades will be implemented during a 9-month shutdown starting in November 2021 and then commissioned with the existing beamlines. In a later stage, the FLASH1 beamline will be modified to an externally seeded beamline supporting the FLASH bunch pattern with a repetition rate of 1 MHz in burst mode. In a 12-month shutdown in 2024 the existing FLASH1 beamline with a length of about 100 m will be completely disassembled and replaced by new components. The future beamline will be composed of multiple sections including a diagnostics section for beam matching. The new FLASH1 will combine seeding with variable gap undulators of APPLE III type, allowing to not only adjust wavelength but also polarization of the generated soft X-ray radiation.

2.2.1. New Accelerating Modules

The 100 MeV of energy gain required to increase the maximum electron beam energy from the current 1.25 GeV to 1.35 GeV is realized by exchanging the two oldest superconducting accelerating modules at location of ACC2 and ACC3. The new modules use modern XFEL-type cryostats. Each module has eight high gradient nine-cell superconducting cavities and includes modern piezo-tuners with remote-controlled adjustment of the cavity tune along the electron bunch train. In addition, the high-power RF coupler’s quality factor will be remote controllable. These features are already applied in all other modules. In parallel to the module exchange, also the RF power waveguide distribution will be tailored to the individual performance of each cavity using tunable Shunt-Tees. To optimize RF-performance, a new RF-station powering the new modules will be located as close as possible to the modules.

As a result of these upgrades, the total on-crest gain for the new ACC2 and ACC3 will be 447 MeV (27 MV/m average maximum cavity gradient). When using the nominal phases required for compression, this would allow increasing the beam energy at the second bunch compressor to 550 MeV and reaching the goal of 1.35 GeV maximum beam energy in operation.

2.2.2. New Bunch Compressors

The current FLASH1 accelerator uses a long 6-dipole S-type chicane [61–63] as the last compression stage. Recently, an additional bunch compressor section was added to the FLASH2 beamline to apply more flexible compression schemes that reduce the peak current in the extraction section from the FLASH linac to the FLASH2 beamline. Therefore, the final compression for FLASH2 is performed just before the undulator section, which leads to better overall electron and SASE performance. As part of the upgrade plans, the S-type compression section is redesigned to improve the overall compression in the
FLASH machine, increase the flexibility of compression schemes, and realize an additional second matching section.

To accommodate the beam emittance and optics measurement devices, the S-type chicane will be replaced by a shorter 4-dipole D-type chicane (BC2 in Figure 1). The need to balance the request for moderately compressed bunches, with reduced micro-bunching, for seeding (∼600–800 A) and stronger compression (∼1–2 kA) with significant residual energy chirp for the ultra-short SASE bunches, requires a flexible chicane design which is capable of a variable momentum compaction $R_{56}$.

![Figure 1](image.png)

Figure 1. Sketch of the FLASH linac with planned laser heater (LH) and new bunch compressors (BC1, BC2) and the energy gain after the FLASH2020+ upgrade.

With the design of the new chicane [64], it has also been considered to allow a correction of the existing intra-bunch transverse to longitudinal correlation. Such a correlation, deriving from wake-fields and coupler kicks, has been demonstrated to be detrimental to the FEL performance, and its effect is expected to be more evident with seeding. With a horizontally movable vacuum chamber, quadrupole/skew-quadrupole packs in the legs of the chicane will be used for correcting such longitudinal to transverse correlations [64–66]. The new bunch compressor chicane design foresees the two inner dipoles mounted on a girder, which can be moved horizontally on rails, therefore enabling bending angles ranging continuously from 0 to 6° or equivalently an $R_{56}$ from 0 to 100 mm. Microbunching instability has been demonstrated to be critical for the operations of seeded FEL. A non-controlled microbunching leads to strong reductions of the FEL intensity but also to a significant deterioration of the spectral quality. Due to such a high sensitivity to microbunching, existing seeded FEL have shown to better operate with beams compressed in a single bunch compressor. Both FERMI and the Shanghai soft X-ray user facility have experienced reduced FEL performance when operating the accelerator with two bunch compressors [67,68]. To verify that the double stage compression scheme designed for FLASH2020+ will be capable of supporting external seeding, dedicated numerical and analytical studies of microbunching amplification along the linac have been performed [69–71].

Our studies (Figure 2) show that with a small energy spread introduced by the laser heater, the microbunching gain at the end of the linac is limited to a few tens for the FLASH2020+ design and comparable to the one estimated for the typical configuration of the FERMI linac [72]. The simulation results also show that FLASH2020+ double compressor scheme does not exhibit the high gain expected at FERMI when operated with two bunch compressors [73].
2.2.3. Laser Heater

Our dedicated beam dynamic simulations predict that with the linac settings planned for the FLASH2020+, induced energy spread in the range 5–20 keV is required to suppress the microbunching instability effectively. For this reason, the installation of a Laser Heater (LH) system is foreseen in the FLASH injector. Contrary to other LH systems installed in other FEL facilities [74,75], the setup designed for FLASH follows the original proposal [76] and will be installed downstream of the first accelerating module and 3rd harmonic linearizer [77]. Since the undulator is located in the straight section of the beamline it can be placed directly upstream of the first bunch compressor of the big chicane. The large momentum compaction ($R_{56} = 140$ mm) combined with the short wavelength of the laser (532 nm) leads to efficient smearing of the imprinted energy modulation necessary for uncorrelated heating of the electron beam.

To avoid possible injection into the heating process of spurious long wavelength modulations coming from unwanted amplitude modulations of the laser heater pulse [78], the laser has been designed to provide bandwidth-limited output pulses with a length of 11 ps (FWHM) in the IR that will be frequency-doubled to 532 nm by a 2nd-harmonic process. A future upgrade of the laser system to also provide broad bandwidth pulses is under discussion to allow the use of the LH for advanced electron beam phase space manipulations which are aiming at short or multiple pulse generation [79].

3. Echo Enabled Harmonic Generation Seeding

One of the key features of the FLASH2020+ project is to introduce external seeding schemes in the FLASH1 beamline in parallel with the SASE operation at FLASH2. While the basic principle is being proved by experiments using the presently installed Xseed setup [56], full capabilities of seeding supporting user operations in FLASH require a complete redesign of FLASH1. New undulators, which take advantage of the increased beam energy (see Section 2.2) are being designed to keep the present coverage over the spectral range down to 4 nm even with external seeding. Moreover, the new scheme will also provide flexibility to control the FEL polarization using APPLE-III undulators for the final radiator of the new beamline.

Recent results have shown that Echo Enabled Harmonic Generation (EEHG) [80] can be used efficiently to produce highly coherent soft X-ray FEL pulses [81]. The EEHG scheme planned at FLASH uses two UV laser beams, seed laser 1 and seed laser 2 (Figure 3) [41].
Figure 3. Layout of the seeding beamline (side view). Seed laser 1 (Seed1) is injected using the in coupling chicane (R56_0), while seed laser 2 (Seed2) uses the overshearing chicane (R56_1). Bunching chicane (R56_2) is used to convert the energy modulation produced by the two lasers in the two modulators (Mod1,2) into bunching before the beam enters the final radiator (Rad1, ...).

To avoid a change of electron beam energy to modify the FEL radiation wavelength, as is the case for the present fixed-gap undulator system, the new APPLE-III radiators will allow a remote adjustment of the K-parameter in each radiator segment. However, given the limited tuning capabilities of the short period APPLE-III radiators, a minimum of three beam energies are required to cover the whole anticipated spectral range (Table 3). External seeding is completed with two modulators (Table 4) and three chicanes (Table 5) making the electron beam’s interaction with external lasers possible and allowing the necessary manipulation of the electron beam phase space. Two planar long period undulators will be used for resonant interaction of the beam with two UV seed lasers. Details on the laser systems and the laser beam injection chicanes are reported in the next section.

Table 3. Nominal electron beam parameters for seeding operations at different spectral regions.

| Parameter          | Short Wavelengths | Intermediate Wavelengths | Long Wavelengths | Units |
|--------------------|-------------------|--------------------------|------------------|-------|
| FEL wavelength     | 4–15              | 10–40                    | 30–60            | nm    |
| e-beam energy      | 1.35              | 0.95                     | 0.75             | GeV   |
| Peak current       | 500               | 500                      | 500              | A     |
| Slice energy spread| 150               | 150                      | 150              | keV   |
| Energy chirp       | 15                | 15                       | 15               | MeV/ps|
| Seeding scheme     | EEHG              | EEHG/HGHG                | HGHG             |       |

Table 4. Seeding undulator parameters.

| Parameter | Modulator | Radiator        | Units |
|-----------|-----------|-----------------|-------|
| Period    | 80        | 33              | mm    |
| Length    | 2.4       | 2.4             | m     |
| Type      | Planar    | APPLE III       |       |
| Number    | 2         | 11              |       |

Table 5. Parameter for the 3 chicanes required for the EEHG.

| Parameter                  | In Coupling Chicane | Overshearing Chicane | Bunching Chicane | Units |
|----------------------------|---------------------|----------------------|------------------|-------|
| Length                     | 2.7                 | 6                    | 4.3              | m     |
| Dispersion (R56)           | 0.8                 | 0.45–7               | 0.02–0.2         | mm    |
| Trajectory offset          | 20                  | 20                   | 5                | mm    |

Compared to the existing seeding facilities [6,82], FLASH will, for the first time, implement seeding at a MHz repetition rates. To succeed, some of the seed laser parameters typically used elsewhere must be significantly modified (Table 3). As described in the next section, the two seed lasers will have a central wavelength of around 300 nm and 343 nm. Therefore, it is necessary to operate EEHG at the 75th harmonic for reaching the shortest wavelength (4 nm). Theoretical predictions show that a high degree of bunching
at such a high harmonic can be achieved. Moreover, recent experiments have shown EEHG bunching up to the 100th harmonic [81]. However, continuous EEHG operation of a seeded FEL at such a high harmonic has not yet been demonstrated. For this reason, detailed FEL simulations have been carried out for the case of the shortest anticipated wavelength (4 nm). For the presented setup in the last section, an optimized EEHG at 4 nm with an ideal beam can produce more than 5% initial bunching at the radiator entrance. Such a level of bunching is high enough to overcome the beam shot noise and allow a proper FEL amplification of the coherent signal along the full length of the radiator (Figure 4). With the possibility of using up to 11 undulators, FEL saturation power can be exceeded with the proper tapering of the undulator parameter K. Currently, simulations with ideal beams show that a peak power with optimal tapering of more than 2 GW can be extracted.

The use of a very long radiator (∼10 gain lengths) with a well bunched beam requires a proper undulator tapering to exceed the FEL saturation power (Figure 4b) while maintaining a well-defined and narrow frequency spectrum (Figure 4d). However, the extra power extracted from the electron beam after saturation (at ∼17 m) comes with a slightly increased FEL pulse length with respect to the optimal case (Figure 4c). From ongoing studies, it is also evident that a different optimization of the tapering could be exploited to emphasize the leading super radiant spike and generate very short (a few fs) pulses [85].

Expected FEL parameters for the upgraded FEL confirmed by Genesis [84] FEL simulations are reported in Table 6. Results based on Genesis [84] simulations do not account for the possible sources of bunching deterioration occurring before the FEL process starts.
Only negligible modulations of the electron beam phase space are expected based on recent micro bunching studies along the FLASH2020+ linac [86]. However, previous works have shown that EEHG bunching at very high harmonic can be smeared by intra-beam scattering, incoherent synchrotron radiation, and coherent synchrotron radiation occurring in between the first modulator and the radiator [87–89]. In contrast to other schemes [88], in our setup a second seed laser is used that is much shorter than the electron beam and the first seed laser beam. Consequently, the sensitivity to these effects is significantly reduced and is expected not to affect the bunching content and coherent properties dramatically [90].

Essential studies of the possible parameter fluctuations have started considering the high sensitivity of the final FEL performance on the fine adjustment of the tapering along the radiator beamline.

At longer wavelengths, EEHG can easily generate bunching as high as 10% or more. Consequently, parameters need to be adjusted to keep the bunching at a 5% level to avoid quick over-bunching in the long radiator. Moreover, since the gain length is significantly shorter at the long-wavelength (∼1.2 m at 10 nm), FEL amplification develops much faster in the radiator and makes the undulator tapering crucial [91].

For the 10 nm case, Genesis simulations show that FEL saturation is reached in approximately four radiator sections (Figure 5). Optimization of post saturation FEL dynamics requires an accurate adjustment of the undulator tapering. Otherwise, the pulse profile departs from a Gaussian profile in both the temporal and the spectral domains. Control of the FEL process is important for moving the saturation point downstream in the radiators as is required to keep the FEL source point unchanged while the FEL wavelength is changed.

For the longer wavelengths spectral range (30–60 nm), the simpler High Gain Harmonic Generation scheme (HGHG) [19] will be used while the intermediate range could be reached with both the HGHG and the EEHG schemes. The possibility of operating HGHG with both the first and second seed lasers would give two independent lasers in the two modulators in the near future. Such a system with a split undulator configuration of the radiator allows for two completely wavelength-independent FEL pulses produced out of the same electron bunch. This advanced scheme will open essential opportunities for FEL pump FEL probe experiments.

Table 6. Expected parameters of the external seeded FEL (* these values might be wavelength dependent).

| Parameter                  | Value  | Units |
|----------------------------|--------|-------|
| Wavelength                 | 4–60   | nm    |
| Peak power *               | 0.5–2  | GW    |
| Polarization               | Variable |      |
| Pulse length (FWHM) *      | 10–30  | fs    |
| Energy per pulse *         | 5–20   | µJ    |
4. Seeding Lasers

The possibility to produce highly coherent soft X-ray externally seeded FEL pulses relies on the capability of the seed laser to imprint its coherence properties into the relativistic electrons through the energy modulation. Such a process critically depends on the laser beam quality. While seeded FEL has been demonstrated to be feasible at a low repetition rate [81], its implementation with FLASH’s pulse burst timing structure featuring the in-burst repetition rate of up to 1 MHz is not trivial. In the EEHG mechanism FEL properties, such as wavelength and pulse length, are determined by the second seed laser that is thus required to provide short pulses (50 fs) and tunable wavelength. Moreover, it has also been shown that EEHG spectral properties and coherence critically depend on the quality of the second seed laser beam that is required to be as close as possible to the Fourier limit [92]. The seed laser parameters required for external seeding using the HHGH and EEHG method are summarized in Table 7. The high laser pulse energy required includes some margin to take into account possible losses along the complex laser transport line described in the next section.

The seed laser system being developed in-house starts with a powerful picosecond Yb-amplifier chain. The seed laser 1 is generated with a third harmonic generation stage while seed laser 2 is based on a near infrared optical parametric chirped pulse amplifier (OPCPA) which is pumped by the second harmonic of the Yb-amplifier followed by a cascaded sum frequency generation stage (ccSFG). In the ccSFG stage the OPCPA output is mixed with the near-infrared output of the Yb-amplifier twice in two subsequent stages.
Table 7. Seed laser properties at the modulators.

| Parameter                          | Seed Laser 1 | Seed Laser 2 | Units |
|------------------------------------|--------------|--------------|-------|
| Wavelength                         | 343          | 297–317      | nm    |
| Max. Pulse energy                  | 50           | 16           | µJ    |
| Pulse length (FWHM)                | ~500         | 50           | fs    |
| Spectral width                     |              |              |       |
| Beam radius (1/e^2) at the modulator | 750         | 600         | µm    |
| Rayleigh length                    | 3.4          | 4.0–3.7      | m     |
| Beam quality                       | <1.5         | 1.5          | M^2 TEM00 |
| Pointing stability at the modulator (rms) | 50          | 50           | µm    |
| Polarization                       | Hor.         | Hor.         |       |
| Focus position                     | Modulator 1 center | Modulator 2 center |
| Temporal structure                 | Up to 600 pulses at 1MHz at 10Hz | Up to 600 pulses at 1MHz at 10Hz |

The laser system is based on recent developments for the pump-probe laser installed at the European XFEL where a Yb chirped pulse amplifier (CPA) system comprising a Yb:seed oscillator, a Yb:fiber-laser front-end, and a 5 kW burst-mode Yb:YAG InnoSlab amplifier [93]. The system was developed to drive a near infrared OPCPA. The Yb:CPA system for the seeding laser follows these developments and has two 1030 nm center wavelength outputs: a short pulse output, delivering a 3 MHz train of compressed pulses of 300 fs duration and 5 µJ energy and a high energy output, delivering a 1 MHz train of compressed pulses of 800 fs duration and 4 mJ energy. The burst-length is limited to 600 µs. Longer bursts would lead to significant changes in beam size and pointing of the high energy output due to thermal transients in the InnoSlab amplifiers.

The fixed wavelength of the seed laser 1 pulse is generated straight forward via third harmonic generation of a 0.3 mJ portion of the compressed high energy output. Simulations and preliminary experiments showed that we can generate more than 100 µJ pulse energy of approximately 600 fs duration which fulfils the requirements for the seed laser 1 pulse. The generation of the tunable seed laser 2 relies on an efficient chirped sum frequency generation scheme [94]. First the short IR pulse output drives a white-light supercontinuum which is amplified in a first broad-band non-collinear optical parametric amplifier (NOPA) to more than 300 nJ. These ultra-broadband seed pulses are negatively chirped by dispersive mirrors in order to match the pulse duration of the second harmonic of the high energy output. Their bandwidth supports 50 fs pulses after amplification in two subsequent NOPA stages to more than 200 µJ. The output is tunable between 680 nm and 950 nm by adjusting the delay between seed and pump pulses.

The tunable and negatively chirped OPCPA output is converted by two subsequent cascaded SFG stages with 1 mJ of the 1030 nm high energy output beam to the required UV wavelength range. This scheme supports 50 fs pulses durations at conversion efficiencies of more than 60% with respect to the OPCPA output which is significantly higher than what broad-band frequency doubling or tripling would allow. Since the phase is preserved during the chirped SFG processes, the tunable UV pulses can be compressed by normal dispersion material (e.g., fused silica wedges).

A first proof of principle experiment using comparable pulse energies but at lower repetition rates has confirmed the feasibility of the concept reaching exceptional high UV conversion efficiencies of 69% from the strongly negative chirped OPCPA output pulses with excellent agreement to the simulations [43].

Seed Laser Beamlines

Optimal performance of the seeded FEL poses strict requirements to the seed laser properties at the interaction points with the electron bunches (see Table 7). This imposes the design of a beamline capable of preserving the high-quality laser pulses produced in
the laboratory till the interaction point and methods for constant monitoring and actively control of critical parameters is essential.

After the generation of the seeding lasers in the laser laboratory, the two seed lasers, seed laser 1 and seed laser 2, will be transported to the interaction regions via dedicated laser beamlines. Seed laser 1 travels a distance of $\sim 22$ m from the laser lab to the center of the first modulator, seed laser 2 a distance of $\sim 30$ m to the center of the second modulator.

In-coupling of both lasers to the electron beamline axis in the modulators will be done through injection chicanes (see Figures 3 and 6), allowing the electron beam to safely pass around the in-coupling mirrors. Given the tight constraints of the electron and laser beamline design the injection mirror needs to be placed in both cases into the accelerator ultra-high vacuum.

To mitigate the effect of air turbulences on the seed laser spatial pointing and arrival time, but also to protect the sensitive beam transport optics against chemical substances responsible for reduction of reflectivity over time, the seed laser beams will be transported in vacuum. Based on experiences with transporting high-power UV pulses at the present Xseed experiment at FLASH [56], ultra-high vacuum is chosen instead of low vacuum pressure.

Each of the two seed lasers is generated on one of the arms of the laser table in the laboratory (see Figure 6) and is transported via throughputs of the laser table into the raised floor where the vacuum chambers hosting the beam transport optics are placed.

![Figure 6. Layout of the laser beamlines (top view) going from the laser laboratory to the two interaction points.](image)

Traveling within the vacuum pipes, the two laser pulses pass through 2 m of radiation protection wall that separates the laser laboratory from the accelerator tunnel. The two laser beamlines continue in vacuum with dedicated vacuum chambers installed close to the tunnel floor to minimize vibrations till the two injection boards. A few of the mirrors in the laser beamline will be motorized allowing an active control of the laser pointing at the injection boards. Moreover, the design of the vacuum chamber and mirror holder is aiming at providing also diagnostic capabilities for on-line monitoring of laser pointing and other laser parameters along the beamline.

At the two in-coupling boards, more diagnostics are placed to facilitate the optimization of the laser parameters (the pulse duration, phase front tilt, pulse energy, mode quality, burst structure, pointing, ...) at the interaction points. A small fraction of the laser pulses or, depending on the type of measurement, the complete pulse is planed to be used for monitoring purposes.

To improve the capabilities of controlling the optimal transverse superposition between the laser and the electron beam, the laser beamline design also includes additional diagnostics for the laser beams out-coupled from the electron beamline after the interaction point. Out-coupling of the first laser will be combined with the in-coupling of the second laser occurring in the “smearing chicane”. Out-coupling of the second laser will be done with a proper design of the bunching chicane. The out-coupling of both lasers will provide further opportunities for monitoring and controlling of the seed laser position and pointing...
along the burst of the pulses in the pulse train. Furthermore, feedback implementation would be possible based on the measured positions at the out-coupling and in-coupling stations. A similar concept is under development at FERMI to improve the laser pointing and consequently the FEL stability.

The possibility to directly measure laser parameters such as the beam energy at the end of the beamline is an important tool that not only provides the information of the seed laser power used in the seeding process but also allows monitoring the transmission through the whole beamline.

With respect to existing seeded FEL facilities [6,82,95] the high repetition rate and high duty cycle of the seed lasers (Table 7) pose major challenges on the design of the beamlines in terms of laser induced damage threshold (LIDT) of optical elements. The available dielectric coating can offer up to 10 J/cm² LIDT, but effects such as the high repetition rate and the very short pulses leading to high peak power needs to be studied. Most critical elements for LIDT are the two injection mirrors where the laser beams are already close (∼3 m) to the focal point placed in the center of the two modulators.

With the goal of reducing the energy density exposed on optical elements, the electron beamline has been designed such that the distance between the injection mirrors and the modulators is as large as reasonably possible. Moreover, grazing incidence mirrors are planned in order to reduce the power density and improve the mirror reflectivity. Given the required horizontal polarization at the modulators, injection of the laser will done on the vertical plane and s-polarization reflection will be used in the last injection mirror.

For the last injection mirrors, one needs to consider that the optical element will be very close to the electron beam axis with a few mm offset. Radiation produced by the highly energetic electron beam passing very close to the optical elements may induce damages. Careful studies of possible radiation damages of optical elements are planned in the near future at FLASH.

5. Conclusions

To better serve the increasing demands of the scientific community, the FLASH free-electron laser user facility operated by DESY in Hamburg (Germany) is undergoing a major upgrade. With the ongoing upgrade of the accelerator, higher photon energies will become available together with improved control of the FEL pulse properties. The newly designed seeded FEL line in FLASH1 will, for the first time, allow the generation of highly coherent pulses at MHz repetition rate. Main changes to the facility are presented together with a discussion on the expected performance for the new FEL that will open essential possibilities to scientists requiring stable and reproducible pulses in the soft-X-ray spectral range.

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Abbreviations

The following abbreviations are used in this manuscript:

- CPA: chirped pulse amplifier
- EEHG: Echo Enabled Harmonic Generation
- EUV: Extended Ultra Violet
- FEL: Free-electron laser
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