ISBN: 978-3-95450-220-2 ISSN: 2673-5474 doi: 10.18429/JACoW-FEL2022-TUP42

STATUS OF THE SEEDING UPGRADE FOR FLASH2020+ PROJECT

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Abstract

In the framework of the FLASH2020+ project, the FLASH1 beamline will be upgraded to deliver seeded FEL pulses for users. This upgrade will be achieved by combining high gain harmonic generation and echo-enabled harmonic generation with a wide-range wavelength–tunable seed laser, to efficiently cover the 60-4 nm wavelength range. The undulator chain will also be refurbished entirely using new radiators based on the APPLE- III design, allowing for polarization control of the generated light beams. With the superconducting linac of FLASH delivering electron beams at MHz repetition rate in burst mode, laser systems are being developed to seed at full repetition rates. In the contribution, we will report about the progress of the project.

INTRODUCTION

In the context of the FLASH2020+ project, the whole FLASH machine is undergoing a notable series of upgrades and refurbishments that include the installation of a laser heater, exchange of bunch compressor chicanes as well as an electron beam energy upgrade. They will be realized during two long shutdown periods, the first ending in August 2022 and the next one scheduled for July 2025.

Full seeding capabilities will be implemented at the FLASH1 beamline to provide users with fully coherent and stable FEL radiation at the Fourier limit, with continuous wavelength tunability below 40 nm and full wavelength range spanning from 60 to 4 nm. Polarization control will also be available. All of the above, combined with the high burst repetition rate of FLASH, will provide the user community with a unique lightsource in the VUV soft-X-ray wavelength range.

In Fig. 1, the envisioned FLASH footprint at the end of the upgrade project FLASH2020+ [1] is shown. The machine operation concept will rely on the a single superconducting linac feeding both FEL beamlines in parallel. The bunch properties will need to be compatible both with seeded and SASE operation on FLASH2. To achieve this, a large linear energy chirp will be present for FLASH1 in order to allow for further compression in FLASH2, as well as downstream FLASH1 for THz production. Such operational mode was already successfully demonstrated last year [2].

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To implement seeding in FLASH1, we anticipate to utilize two harmonic generation seeding approaches for efficiently cover the tuning range for users, namely HGHG [3] and EEHG [4]. For the longer wavelengths (>20 nm), we foresee to employ HGHG. In fact, by looking at the bunching curve as a function of the harmonic number as reported in Fig. 2, one can observe the higher efficiency in generating coherent bunching of HGHG than for EEHG in this wavelength range.. For harmonic numbers $\gtrsim 15$, i.e., for shorter wavelengths, we plan to rely on EEHG.

Such an ambitious upgrade requires new dedicated state-of-the-art seed lasers and laser transport beamlines, new modulators and radiators undulators, magnetic chicanes, as well as numerical simulations to investigate and optimize the setup.

SIMULATIONS

An extensive series of numerical simulations have been performed for optimizing the setup, using different numerical codes. For the electron part we used a combination of elegant [5] and selav [6], that provide fast exploration of the electron beam properties considering collective effects along the linac. Up to now the input beam distribution has been self-generated, but we plan in the next few months to start using realistic beam distributions generated via ASTRA [7]. For the FEL process we use GENESIS1.3v4 code [8]. The seed laser is also fully simulated using [9].

Three different working points, with electron beam energies of 750, 950 and 1350 MeV, represent our baseline. We plan to have full start-to-end simulations for the linac and FLASH1 beamline soon. For this, we developed a comprehensive toolkit with handshaking between the different codes [10]. Such an approach allows for investigating the impact on the FEL output of different machine parameters. As an example, we evaluated the impact of the large residual linear energy chirp needed for parallel operation on the performance of both HGHG and EEHG. By proper tuning of the resonances, we were able to recover similar FEL pulses as in the case when the beam is flat. We also investigated the power jitter variations of the two seed lasers on the EEHG scheme [11]. We also benchmarked EEHG performance using elegant, in particular to investigate the impact of collective effects, e.g. CSR, on the output radiation properties [12]. Concerning the choice of seeding technique to utilize around the transition in efficiency, see Fig. 2, we performed simula-

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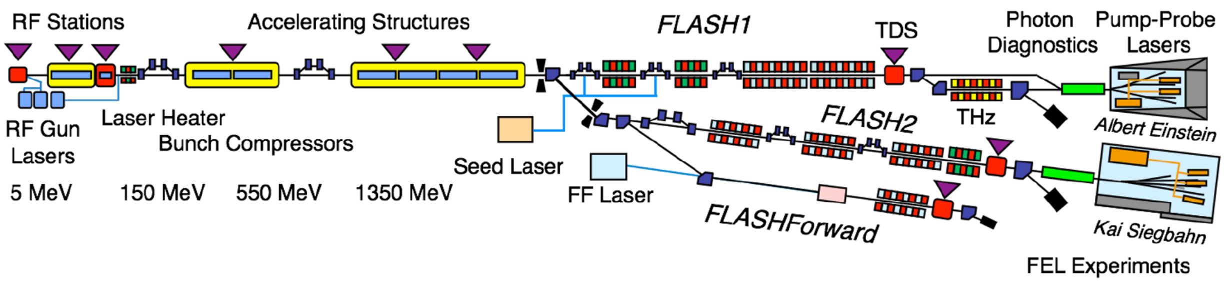

Figure 1: Envisioned FLASH footprint at the end of FLASH2020+ project. The whole machine will undergo a notable series of upgrades and refurbishments, including the installation of a laser heater, exchange of bunch compressor chicanes as well as an electron beam energy upgrade. Full seeding capabilities will be implemented in the FLASH1 beamline.

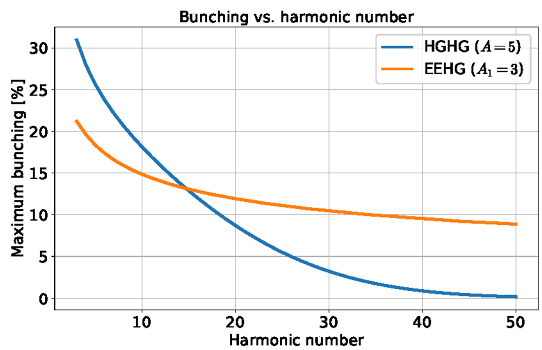

Figure 2: Comparison of the maximum obtainable bunching factor for HGHG and EEHG, according to the equations in [3, 4]. One can notice that for harmonic numbers $\gtrsim 15$, i.e., for shorter wavelengths, EEHG has significantly higher bunching, with reduced energy spread for better amplification. Parameters for HGHG: modulation amplitude $A = 5$, chicane strength B optimized for maximum bunching. Parameters for EEHG: $A_1 = 3$, $B_1 = 32.1$, A_2 and B_2 optimized for maximum bunching.

tions and numerical calculations looking at the performance of EEHG and HGHG [13].

SEED LASERS

A tunable seed laser system is needed in order to have tunable seeded FEL radiation. We will use an OPCPA based system with wavelengths between 297 and 317 nm, allowing for FEL emission in a gap-free spectrum below 40 nm, see Fig. 3.

In the case of EEHG, the first seed will be operated at fixed wavelength of 343 nm. It will be a part of the laser at the end of amplification, branched before seeding the OPCPA. We envision to have the tunable laser almost always on the second modulator, closer to the radiators in order to reduce possible space charge effects when transporting microbunched beams [14].

The parameters for both seed lasers are specified keeping in mind that the beamline will need to provide stable FEL radiation for users in a reliable manner. Hence, it requires

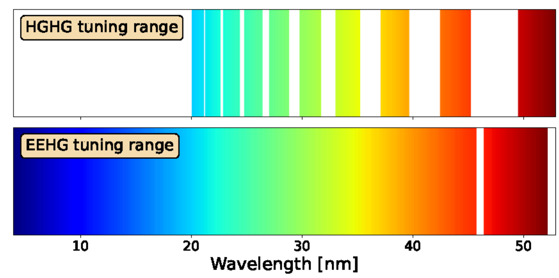

Figure 3: Comparison of the tuning range for the seeded FLASH1 beamline in the case of HGHG and EEHG. Using a seed laser with tuning range of 297–317 nm allows full continuous tunability in EEHG for wavelengths shorter than 40 nm. In the case of EEHG, $n = [-1, -2, -3]$ are considered.

a robust laser system with limited time available for maintenance, as this will generate operational downtimes. The laser system needs to match the repetition rate of FLASH, 10 Hz, as well as the train at 1 MHz internal repetition rate, to realize a fully seeded, high repetition rate source. The pulse duration of Seed1 will be fixed at 500 fs, while Seed2 will be much shorter, on the order of 50 fs as it determines the FEL pulse duration. The chirp for Seed2, which directly influences the output properties of the FEL radiation, will need to be minimized and to stay as constant as possible when changing the laser wavelength. The beam size at the interaction point, located in the middle of each modulator, will be on the order of 600 µm, larger than the electron beam in order to accommodate possible transverse jitters. The transverse position will need to be maintained stable, with maximum variation of 50 µm (rms). The timing stability will need to be better than 50 fs between both lasers, and between the lasers and the electron beam. To satisfy these requirements, both the transverse and the longitudinal alignments will be maintained using feedback loops.

The required wavelength stability for Seed2 will be on the order of 2×10^{-4}, while the time required for wavelength changes less than 10 s for 5% of the tunability range, and 2 minutes for the full wavelength range. This will enable users to perform quick wavelength scans using the FEL radiation. Both lasers will need to deliver hundreds of MW power

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for satisfying the seeding requirements. As the laser power fluctuations directly induce FEL output power fluctuations, the seed lasers need to be stable within 2% shot-to-shot and within 4% train-to-train.

The laser system is partially already running for testing and development, in the newly constructed seed laser laboratory located at the FLASH2 extraction. For further details about the laser systems, see [15].

SEED LASER TRANSPORT

We plan to define a handshake position for each of the two seed lasers, located on the laser table in the laser laboratory. The transport will deliver the laser pulses using full Rayleigh imaging from this location till the center of the corresponding modulator. The full laser transport will be enclosed in UHV environment, in order to minimize both the contamination on the optics, as well as to preserve the laser beam properties from degradation due to nonlinear effects.

We will try to maintain the system as simple as possible, reducing the amount of optics and motors inside the tunnel. The optics will be optimized for maximum reflectivity in the wavelength range and specific for each of the seed lasers. The last mirror for each of the two injections will be in machine vacuum, mounted on a remotely controlled manipulator to allow for establish and maintain the transverse alignment between the electrons and the laser. We investigated in a dedicated experiment the minimum distances from the electron beam that will be required to not induce surface charge accumulation, which in turn would negatively impact the trajectory stability.

In the case of Seed2, due to damage threshold concerns, we will utilize different concepts to reduce the risk of damaging the optics and increasing the downtime for users. We will employ both multi-reflection setups, as well as very shallow incidence angles to increase the effective beam size on the optics themselves, thus reducing the effective peak intensity.

For further details concerning the laser transport, see [16].

UNDULATORS AND CHICANES

The whole FLASH1 beamline will be refurbished and most of the undulators will be exchanged. The two modulators will be two identical undulators, longer than the ones presently used for the Xseed project [17] and with adequate periodicity for ensure optimal resonance along the whole seed laser tuning range. We foresee the installation of at least three magnetic chicanes, bending the beam in the vertical direction. They will be used to create the required offset with the electron beam, allowing for the injection of the two seed lasers for EEHG in the corresponding modulators, as well as to provide the tunable longitudinal dispersion required. When using HGHG we plan to simply close the shutter of Seed1 and open modulator1, as well as set the sheering chicane straight. This allows for maintaining the tunable laser on modulator2, hence obtaining tunable seeded FEL radiation in the longer wavelength range. We will keep the option of delivering Seed2 in the first modulator to explore advanced modes, based, e.g., on the optical klystron scheme [18, 19].

For the radiators, we plan to utilize 2.5 m APPLE-III type devices to provide users with variable polarization FEL radiation [20] along the full wavelength range of the beamline. The beamline has sufficient length for 11 cells for possible radiators and will initially be filled depending on budget constraints. Also in the initial phase, we plan to re-use the existing planar devices presently installed for the Xseed experiments for beam transport purposes.

To simplify operations at longer wavelengths, e.g., by shifting the source position towards the users and reduce possible clipping due to the beam pipe, we plan to install further magnetic chicanes in possible empty slots along the beamline. This will also allow us to further explore advanced FEL modes. For further information concerning the undulator beamline design, see [21].

CONCLUSION

We presented the status of the upgrade towards full seeded FLASH1 in the context of the FLASH2020+ project. The progress in the design and realization of the components is on schedule. The installation of the required components will start in 2024 and we foresee the commissioning to start taking place with the 2025 FLASH restart.

FLASH1 will be a unique lightsource, capable of providing users with high repetition, fully coherent and stable FEL radiation with polarization control, at the Fourier limit in the VUV soft-X-rays from 60 to 4 nm.

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