Tunable UV Laser for External Seeding of the High Repetition Rate Soft X-ray Free Electron Laser FLASH

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Abstract: We are currently developing a tunable high-repetition rate femtosecond UV laser system for external seeding superconducting soft X-ray Free Electron Laser FLASH. Initial results show excellent power and wavelength stability of the Optical Parametric Chirped Pulse Amplification system.

The superconducting free-electron laser in Hamburg, FLASH, is the worldwide first extreme ultra-violet and soft X-ray free-electron laser (XFEL) user facility and has been continuously upgraded since its start in 2005. The current FLASH2020+ upgrade program [1] is implementing 1 MHz repetition rate external seeding, and FLASH will be in fall 2025 after a one-year shutdown the worldwide first externally seeded superconducting accelerator XFEL facility, which will have huge advantages for XFEL science users. For example, we expect temporally coherent X-ray radiation, narrow bandwidth output and significantly less pulse-to-pulse energy fluctuations.

Here we report on the progress in developing a 1 MHz seed-laser source for this upgrade project, which requires two UV pulses seed-1 and seed-2 overlapping with an 1.35 GeV electron beam for Echo Enabled Harmonic Generation (EEHG) seeding (similar to the 50 Hz repetition rate FEL FERMI [2]): The requirements for the seed pulses are respectively a center wavelength of 343 nm and tunable 297 nm to 317 nm (stability requirement 0.02%), a FWHM pulse duration of 500 fs and 50 fs and a pulse energy of 50 µJ and 16 µJ. Both beams are required to overlap the electron beam with $1/e^2$ a waist radius of 600 µm at a repetition frequency of 1 MHz (600 µs long bursts at 10 Hz burst repetition frequency).

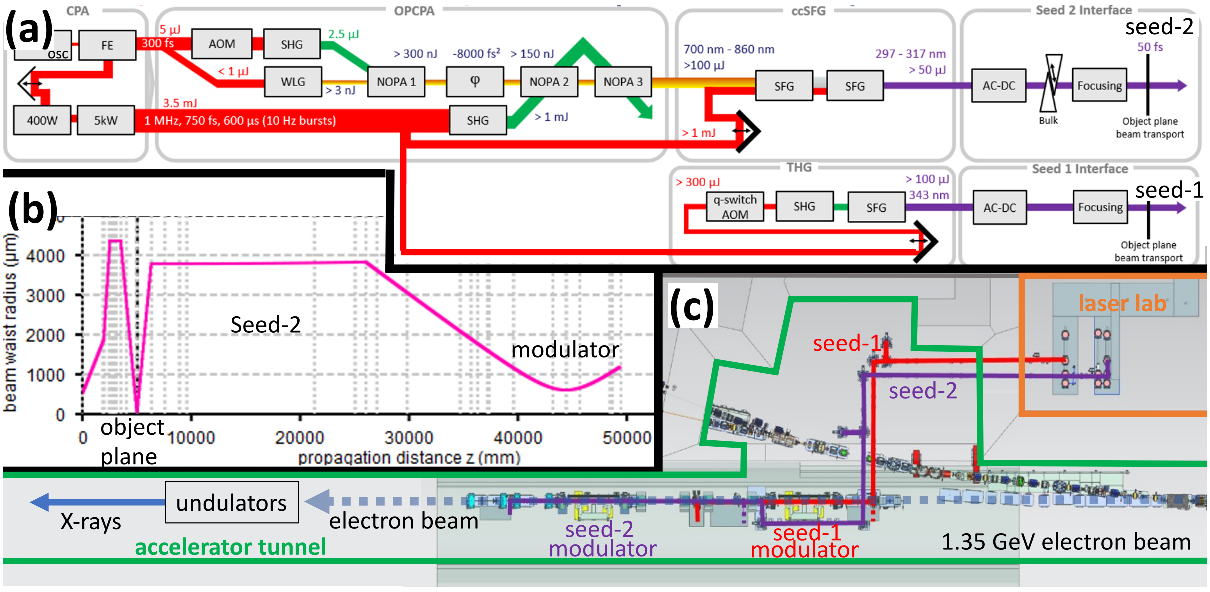

Fig. 1: (a) Schematic of the SLASH laser at FLASH. OSC: oscillator; FE: Fiber Laser Front-End; 400W / 5kW: Innoslab Yb:YAG amplifiers; AOM: Acousto-Optic-Modulator; SHG: Second-Harmonic Generation; WLG: Supercontinuum Generation; NOPA: Noncollinear-Optical-Parametric-Amplifier; φ: negative dispersion (chirped mirrors); SFG: Sum-Frequency-Generation; AC-DC: Astigmatism-Compensated-Distance-Constant Telescope; Bulk: fused silica material for dispersion compensation. (b) beam transport optics for seed-2 (seed-1 optics is similar) : An object plane in the laser lab is relay-imaged over more than 40 m to the center of the electron-modulator magnetic structure with ~factor 15 magnification in a vacuum beam transport line. The vertical lines correspond to location of mirrors, windows and the modulator dimensions. (c) Schematic of the laser beam-transport from the laser lab to overlap the electron beam in a modulator structure. Only the laser lab is accessible during accelerator operation.

To meet these requirements, we are setting up the laser system SLASH (Seeding Laser for FLASH) which is schematically illustrated in Fig.1(a). We installed fiber-laser front-end seeding a high repetition rate Yb:YAG laser system which can provide an 1030 nm near infrared (NIR) output power of ~4 kW after compression to 750 fs FWHM during a the 600 µs long burst perfect synchronization to the accelerator main RF oscillator and burst timing. This laser system is split in three parts: (1) a ~ 300 µJ part of the beam is used for third harmonic generation – supplying seed-1. (2) Approximately 2 mJ of the output is used to drive a noncollinear OPCPA system, similar to [3], providing a tunable NIR output tunable between 700 nm and 860 nm at more than 100 µJ pulse energy, which is stretched to a negative chirp. (3) Approximately 1 mJ of the 1030 nm pulse is used for a two-stage upconversion via sum-frequency generation (SFG) of the tunable NIR pulses to the required seed-2 wavelength range between 297 nm to 317 nm. Both seed-1 and seed-2 beams are focused in-vacuum to an intermediate focus (object plane in Fig 1) with waist radius 40 µm and 100 µm, respectively. This object plane is relay-imaged in a vacuum beam pipe to the center of the magnetic modulator structures where the laser pulses imprint an energy modulation to the up to 1.35 GeV electron beam.

Besides the overall design of laser system and beam transport by now we have completed the laser output for seed-1 and demonstrated the required pulse parameters and stability. For the more challenging seed-2 output we completed the setup for the tunable NIR output will be up-converted to UV and achieved the required pulse energies and pulse durations. FLASH seeding requires excellent stability for the seed lasers. In particular a beam asymmetry of better than 10%, a pulse-to-pulse energy instability better 2% rms, and a wavelength instability of less than 0.02% is needed for seed-2. Thus we tested the performance of our tunable NIR output at 300 µJ pulse energy (required are only 100 µJ). The results as shown in Fig. 2, match predictions of a simulation using the 1030 nm pump-laser parameters as input [4].

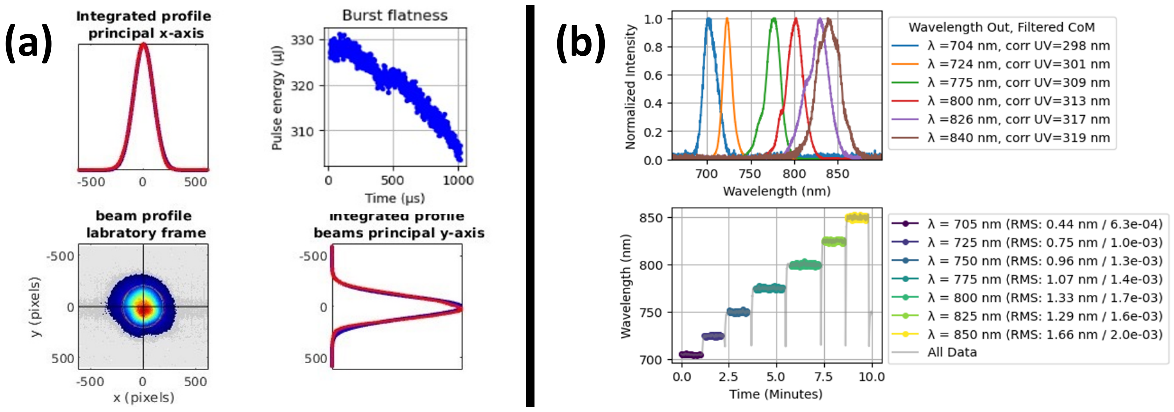

Fig. 2: (a) Measured beam profile and pulse energy of the tunable NIR output for generating seed-2 via up-conversion. Notes: (1) Only 600 µs bursts are required. (2) The pulse-energy shows about a 10% peak-to-peak variation over the 1 ms burst. However, this effect is repetitive from burst-to-burst and can be compensated by controls to the RF power of a AOM in the supercontinuum generation path. The energy stability for an individual pulse in the burst is meeting our requirements. (b) Wavelength tuning of the NIR output (top)- the legend shows the predicted corresponding UV wavelength. Bottom: Wavelength instability.

The pulse energy and tuning range results fulfill our requirements. The obtained wavelength instability (preliminary data) is larger than required, we are currently investigating possible causes. Possible pathways to improvements could be improved control feedback, better dispersion matching or spectral filtering. We are currently in the process of setting up the vacuum system required for tunable UV generation via two-stage cascaded sum-frequency generation.

In summary, we will present the design and the current status of the SLASH laser system, which is near completion. During a shut-down of the FLASH facility from June 2024 to end of July 2025 a tailored electron-beamline for external seeding will be installed together with the seed-laser beam-transport. With everything installed, externally seeded FEL operation is expected in fall 2025 which will make FLASH the worldwide first high-rep-rate XFEL with external seeding.

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[2] P. Rebernik Ribič *et al.*, "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser," *Nat. Photonics*, vol. 13, no. 8, pp. 555–561, Aug. 2019, doi: 10.1038/s41566-019-0427-1.
[3] M. Pergament *et al.*, "High power burst-mode optical parametric amplifier with arbitrary pulse selection," *Opt. Express*, vol. 22, no. 18, p. 22202, Sep. 2014, doi: 10.1364/oe.22.022202.
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