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Novel Photocathode Lasers for the Hard- and Soft- X-ray Free Electron Lasers EuXFEL and FLASH

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Abstract: We developed, constructed and commissioned novel photocathode lasers for the X-ray FELs European XFEL and FLASH which allow emittance optimization via beam shaping. Both facilities operate continuously with those lasers since Jan. 2024 with high uptime and excellent performance.

After completing a five-year development program, we commissioned beginning of 2024 a new type of photocathode laser systems (NExt generAtion Photocathode Laser NEPAL) at the high repetition rate X-ray Free Electron Lasers (XFEL) FLASH (soft X-rays) [1] and European XFEL (EuXFEL, hard X-rays) [2]. Those world-leading facilities enable scientists, for example, to investigate structural biological phenomena with atomic spatial and highest temporal resolution. The photocathode lasers are of crucial importance for the performance of those facilities, since the X-ray production is very sensitive to laser parameters. The NEPAL lasers provide temporal and spatial shaped picosecond deep UV pulses (257 nm, 1 ps to 20 ps, few µJ at up to 4.5 MHz (up to 1 ms long bursts at 10 Hz) allowing the generation of very low emittance electron beams, which are needed for highest X-ray photon energies. At EuXFEL we demonstrated an excellent photoinjector emittance of 0.375 mm mrad at 250 pC and 150 MeV electron charge and energy, respectively which is used for routine operation. Simulations show that the advanced beam shaping capabilities of the NEPAL lasers will both allow to push the X-ray photon-energy beyond 25 keV and to enhance special operation modes, such as attosecond X-ray generation.

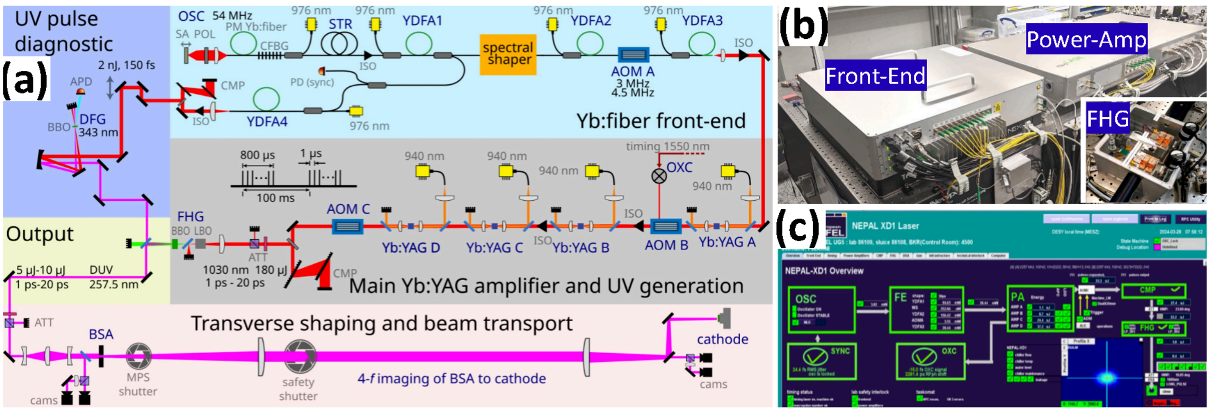

Fig. 1: (a) Schematic of the NEPAL laser at FLASH. OSC: oscillator; SA: saturable absorber; POL: polarizer; CFBG: chirped fiber Bragg grating; STR: passive fiber stetcher ISO: isolator; YDFA: pm-Yb:fiber amplifier; CMP: transmission grating compressor; Yb:YAG: Yb:YAG rod amplifier; PD: photodiode; AOM: acousto-optical modulator; OXC: optical cross-correlator APD: avalanche photodiode; FHG: Forth harmonic gemeration; BBO: beta-Barium borate. LBO: Lithium triborate; DFG: difference frequency generation; ATT: attenuator; BSA: beam-shaping aperture; MPS: machine protection system; cams: camera-based beams-stabilization; cathode: CsTe photocathode at the XFEL gun. (b) Photograph and (c) main laser control panel at EuXFEL.

The set-up (schematic, photographs, control-panel) is shown in Fig. 1. The near-infrared Yb-fiber/Yb:YAG laser system is very similar to a system developed for pump-probe experiments at FLASH [3]. The front-end consists of a pm-Yb-fiber mode locked oscillator a passive fiber stretcher (to ~ 10 ps) and 3-stage Yb-fiber amplifier, which generates a 20 mW pulse train at 1030 nm center wavelength (1 MHz at FLASH, 4.5 MHz at EuXFEL) to seed a 4-stage Yb:YAG power amplifier chain (the power amplifier is provided by neoLASE GmbH). An additional nonlinear Yb-fiber amplifier generates 100 mW, 150 fs which can be used to characterize the UV output via DFG cross-correlation or cross-FROG measurements. The Yb:YAG amplifier chain boosts the laser pulse energy to more than 180 µJ. The front-end contains a programmable high-resolution spectral shaper for temporal pulse shaping. To match the XFEL timing, two acousto-optic modulators are used. A two-stage second harmonic generation setup with LBO and BBO crystals converts the NIR laser to 257.5 nm. The generated electron bunch charge at the photocathode can be set by two control elements: A polarizer-waveplate combination can attenuate the UV output – this element is used for slow bunch-charge feedback. Additionally, the RF-power to an acousto-optical modulator for pulse-picking (AOM C in Fig1) can control the individual bunch-charge. This control element is typically used to ensure that the electron-bunch train is flat in charge. However, any arbitrary charge patterns are possible and are used for special operation modes. The timing of the output-pulses needs to be synchronized to both the accelerator RF phase and to the electron-bunch pulse pattern requested for the facility. This is ensured by phase-locking the oscillator to the facility main RF oscillator and by timing all AOMs according to the facility-wide distributed bunch pattern using field-programmable-gate-arrays (FPGA). Slow timing drifts are compensated by using an optical cross correlator signal (OXC in Fig.1) to the facility-wide pulsed-laser timing system which utilized length-stabilized optical fibers [4]. The UV pulses are spatially shaped via a circular aperture (size flexible) which is imaged to the photocathode (~ 20 m distance at EuXFEL).

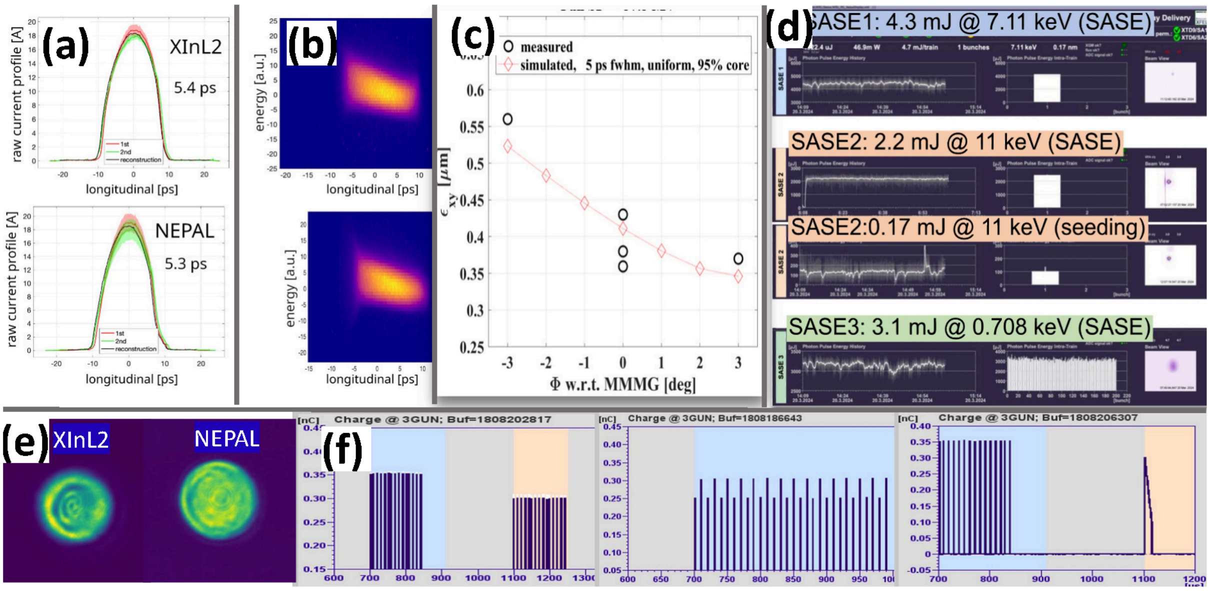

Fig. 2: (a), (b), (e) Matching of the temporal and spatial electron-bunch and laser profile of the EuXFEL injector using the NEPAL photocathode laser to the existing Nd:YVO4-based laser system XInL2. (a) Current profile and (b) corresponding electron energy profile measured by a transverse-deflecting RF-structure in the EuXFEL injector section. (e) transverse beam profile (image of circular aperture) at a camera on equivalent plane to the photocathode. Note: circular fringes are caused by clipping of Fourier-orders in the transport beam-pipe. (c) Simulated (red circles) and measured (black circles) emittance for a 250 pC electron bunch as function of the electron gun RF phase. (d) Screen-shots of a typical performance of the three XFEL beamlines of EuXFEL with the NEPAL photocathode laser. (f) Various electron bunch patterns generated with the NEPAL lasers at FLASH.

In 2023 we installed two NEPAL laser systems at FLASH, one at EuXFEL and one at DESY's photoinjector test facility PITZ. At the time of the conference, a fifth system will be installed at EuXFEL which will be used as hot spare. The commissioning of the laser systems was done in both facilities in January 2024, when the XFELs were started up after a scheduled shutdown. Fig 2 shows selected injector and XFEL performance of the EuXFEL facility. Here we used the temporal shaping capability of the NEPAL laser system to match the electron beam properties to the existing $Nd:YVO_4$-based photocathode laser XInL2 which has fixed temporal shape. This allowed for tuning using known accelerator set-points as starting values and enables fast switching of photocathode lasers with minimal accelerator tuning in case of laser failures. At both facilities the two NEPAL-lasers combined via polarization multiplexing and can be used simultaneously. At EuXFEL the old XInL2 can be additionally added via wavelength multiplexing. The multiplexing capability provides redundancy and allows for special XFEL operation modes which require two simultaneous laser pulses. Fig 2c) shows the simulated and measured transverse projected emittance for a 250 pC bunch charge at EuXFEL. We achieved an injector emittance of 0.375 mm mrad. While in routine operation only simple pulse-shaping is used (changing duration of Gaussian pulses via amplitude shaping), advanced shaping techniques which also use the phase-shaping capabilities of our pulse-shaper for injector emittance optimization are explored in a R&D project.

In conclusion, we developed and installed new photocathode laser systems for the soft- and hard X-ray FELs FLASH and EuXFEL, which are now used for routine operation with excellent performance and availability. The new Yb-fiber / Yb:YAG based laser-system NEPAL allows for advanced controls, most prominently temporal pulse shaping. This feature will extend the X-ray capabilities of the facilities in the near future.

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