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PHOTOCATHODE LASER DEVELOPMENT FOR SUPERCONDUCTING X-RAY FREE ELECTRON LASERS AT DESY

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Abstract

We present an ultrafast laser system for driving the photocathode electron guns at the FLASH and the European XFEL facilities in Hamburg, Germany, which can be operated at a variety of laser pulse durations and pulse shapes, matched to the needs for optimum X-ray generation at different FEL operation modes.

INTRODUCTION

Modern X-ray Free-Electron Lasers (XFEL) are a key tool to enable a variety of scientific research such as atom molecular optic experiments, condense matter experiments and X-ray spectroscopy [1]. Those large-scale facilities rely on robust and reliable ultrafast deep ultraviolet (DUV) lasers to drive electrons from their RF photocathode gun. In this contribution we present a new photocathode drive laser NEPAL (NExt generation PhotocAthode Laser), which offers more flexibility in duration and shape of the 257.5 nm picosecond pulses for driving the CsTe Photocathodes of DESYs superconducting burst-mode XFELs FLASH and EuXFEL [2, 3]. The laser matches DESY's FEL bunch structure: Up to 800µs long bursts at up to 4.5 MHz intraburst-rate with 10 Hz burst repetition rate. In the current version, the system will offer variable Gaussian shaped DUV pulse durations, tunable from 1 ps to 20 ps to address different operational regimes of the XFEL, e.g. short low charge bunches for single-spike Self-amplified Spontaneous Emissionoperation and long high-charge bunches for regular operation, optimized for highest X-ray pulse energies. Since the laser system comprises a high-resolution spectral intensity and phase shaper, it is also capable of generating flat-top DUV pulses, which are beneficial for reducing electron-beam emittance. This feature will be studied in an initial R&D phase and later implemented for routine operation. The laser is constructed in a hybrid architecture consisting of Yb:fiber and Yb:YAG solid state near infrared (NIR) gain blocks and nonlinear crystals for frequency conversion to DUV. Here, we present a prototype version of the laser, which delivers DUV pulses of 11.5 µJ energy and 17.4 ps (FWHM) duration when set to long pulse mode and pulses of 6.15 µJ energy and 1.05 ps (FWHM) duration when set to short pulse mode. In both operation modes the pulses are nearly transform limited with a beam quality $M^2 < 1.3$ and an RMS pulse energy fluctuation smaller than 0.3%.

LASER SYSTEM

The first version of the laser is designed for the FLASH FEL facility in DESY Hamburg within the project of FLASH2020+ [4], the worldwide first externally seeded high repetition rate soft X-ray free electron laser. The laser parameters are set to match the requirements of the FEL for different operation modes. A block diagram of the laser system is shown in Fig. 1. The system consists of two identical DUV laser branches NEPAL-F_1 and NEPAL-F_2, which can operate in different pulse modes, repetition rates and spatial beam sizes for the respective needs of the two FEL beamlines FLASH1 and FLASH2. The branches are polarization combined to drive the common linear accelerator. The combined beam can provide an up to 1 ms long burst in 10 Hz with up to 1 MHz intra-burst repetition rate. Since at FLASH the electron bunches cannot be dumped before the FEL beamlines, a 50-70 µs gap in the burst is required for switching between the FEL beamlines.

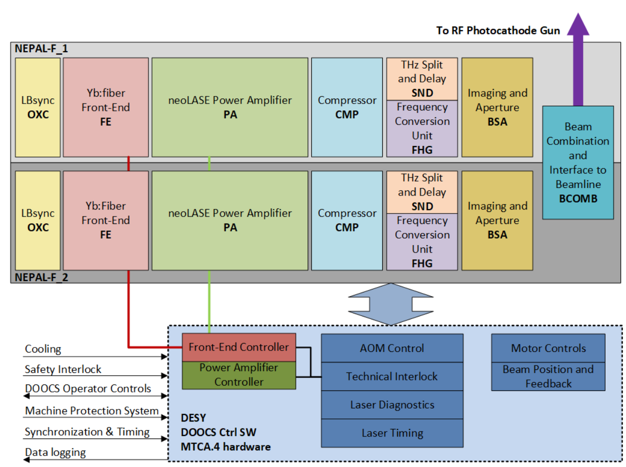

Figure 1: System diagram of the NEPAL-F laser system. The system is composed of two identical laser lines NEPAL-F_1 and NEPAL-F_2 comprising the sub-components Optical Cross Correlator (OXC), Front-End (FE), Power Amplifier (PA), Compressor (CMP), Split and Delay unit (SND), Frequency conversion (FHG), Beam Shaping Aperture (BSA) and Beam Combination (BCOMB).The laser parameters such as pulse duration, delay, spectrum and phase, burst length and intra-burst repetition rate are remotely controllable via Distribute Object-oriented Control System (DOOCS) [5].

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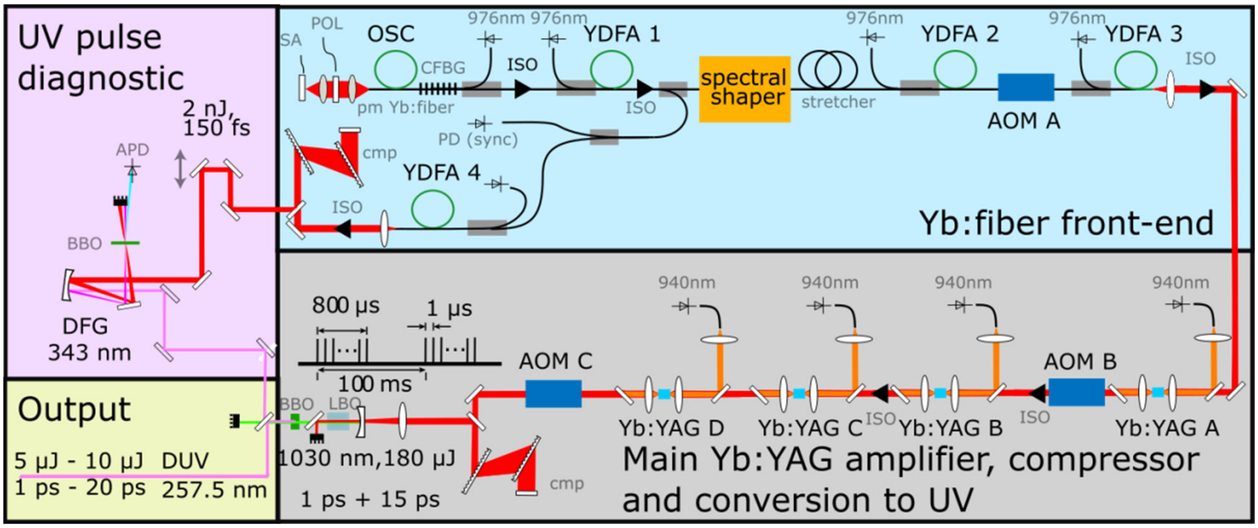

Figure 2: Schematic of one laser branch NEPAL-Fx: SA: Saturable absorber, POL: polarizer, CFBG: Chirp Fiber Bragg Grating, YDFA: Ytterbium doped fiber amplifier ISO: Isolator, AOM: Acoustic Optic Modulator, cmp: compressor, APD: avalanche photodiode.

Figure 2 shows the details of one single NEPAL-Fx branch, It consists of the following building blocks: Yb: fiber front-end, Main Yb: YAG solid-state amplifier, pulse compressor, and nonlinear conversion to DUV. Additionally, a DUV-NIR difference frequency generation (DFG) cross correlator is installed for pulse diagnostics. It uses a compressed 0.2 ps NIR pulse train from the front-end as reference.

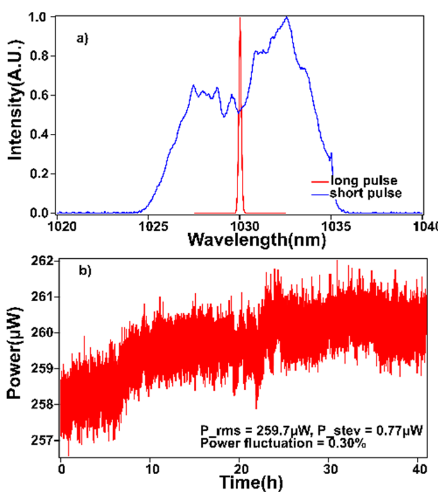

Figure 3: spectrum of the front-end output and power fluctuation (sampling rate: 3.3 Hz).

The fiber front-end consists of a picosecond-fiber oscillator [6], and four Yb: fiber amplifiers (approx. 20 dB gain each). The pulses are stretched to approx. 25 ps via a 200 m long single-mode fiber and phase- and amplitude- shaped in a programmable high-resolution spectral shaper. An acoustio-optical modulator reduces the repetition frequency to 1 MHz. The detailed design of the front-end can be found in [7, 8]. With different amplitude shaping settings, the laser is able to deliver tuneable spectral bandwidths between 0.05 nm and 6 nm at 1030 nm center wavelength, corresponding to compressed pulse durations of >20 ps and ~500 fs, respectively Figs. 3 a) and 3 b) shows a trend of the average power as measured over 40 hours. The power fluctuation is less than 0.3%.

The main amplifier consists of four Yb: YAG crystals. While the first amplifier is continuously pumped, the three following amplifiers are pulsed pumped for burst amplification. The 1.2 ms long bursts are cut out by a second AOM after the first amplifier. A third AOM, which is placed after the final NIR amplification stage is used for energy-flattening of the burst and cutting out individual pulses from the 1 MHz intraburst pulse-train. This feature allows to reduce the intraburst repetition rate and to shape the final burst envelope. The main amplifier is able to deliver pulses of over 180 µJ at 1030 nm center wavelength for both short pulse and long pulse operation mode (Fig. 3 b).

A pair of transmission gratings is used to compensate the residual chirp and compress the pulse down to 900 fs in short pulse mode. In long pulse mode, neither stretcher nor compressor have a significate influence on the pulse duration, due to the narrow optical spectrum.

The compressed laser beam is sent into two cascaded second harmonic generation stages, equipped with Lithium Triborate (LBO) and beta-Barium borate (BBO) nonlinear crystals, respectively. This stage converts the laser wavelength from the amplified 1030 nm NIR pulse-train to 257.5 nm DUV, which is needed at the electron gun. Since two different sets of crystal lengths are required for efficient conversion of short and long 1030 nm pulses, a mechanical crystal exchange mechanism was installed. With 8 mm (2 mm) LBO and 2 mm (0.5 mm) BBO crystal lengths we achieved optimal efficiency for long (short) pulse operation. With using only 50 µJ of our NIR pulse energy, we were able to generate 11.2 µJ (6.1 µJ) DUV pulses of 17.4 ps (1.05 µs) duration for long (short) pulse operation, meeting all FLASH requirements (Fig. 4).

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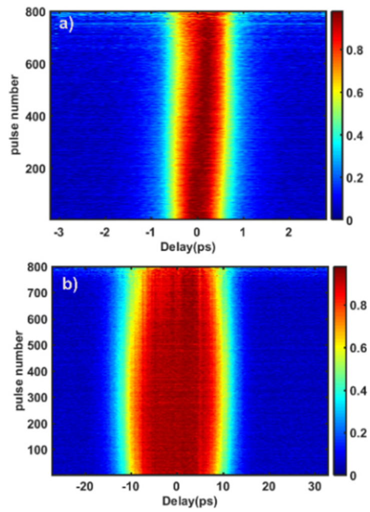

Figure 4: DUV pulse duration characterization by cross-correlation measurement for short pulse operation (a) and long pulse operation (b). Colour bar: Intensity of cross-correlation (normalized).

BURST CONTROL

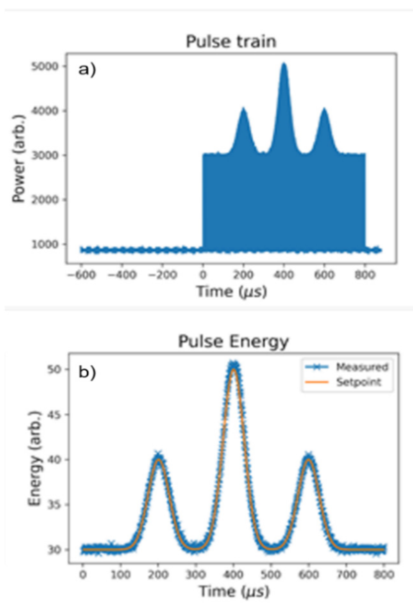

Figure 5: a): The arbitrary generation of pulse train. b): the comparison between the set burst and the measured burst.

The amplitude of the laser pulses along the burst can be shaped arbitrarily (Fig. 5). This is realized by an adaptive feed forward scheme using an iterative learning control algorithm [9] acting on AOM C and the pump current of amplifier D. The necessary timing parameters are given by the DOOCS control system.

CONCLUSION

In this proceeding we report the photocathode laser system NEPAL developed for flexible operation of the DUV driven guns of the X-ray FEL facilities FLASH and European XFEL in Hamburg, Germany. With a reliable Yb: fiber front-end, an Yb: YAG power amplifier and a common path fourth harmonic generation set-up, the laser delivers all required pulse parameters for accelerator operation. A programmable spectral amplitude and phase shaper in the NIR front-end enables fast switching between short and long DUV pulse durations matched to specific accelerator needs and will in future even enable advanced emittance optimization via temporal flat-top pulses. We believe that the laser fulfils all requirements for long-term high-availability gun operation. We have already the NIR part of the laser in 24/7 operation as part of the FLASH1 pump-probe laser [8, 10]. A prototype version of the laser fulfils all requirements for the upcoming upgrade of the FLASH facility, where we plan to install NEPAL-laser systems in 2022.

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