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THE EUROPEAN XFEL PHOTOCATHODE LASER

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Abstract

We present the design, performance and long-term stability of the hybrid Yb:fiber, Nd:YVO_4 laser system used to drive the RF photocathode gun and laser heater at the European XFEL facility. The laser system provides deep UV output pulses in 600 µs long bursts of laser pulses with variable intra-burst repetition rates ranging from 500 kHz to 4.5 MHz. Due to its robust laser architecture, comprised of a mode-locked and synchronized Yb:fiber oscillator, Yb:fiber pre-amplifiers and Nd:YVO_4 power amplifiers, the laser has operated with >99% uptime since January 2017. Using this laser system, the European XFEL reported landmark electron beam energies of 17.5 GeV in July 2018, and simultaneous multi-mJ lasing in its three SASE beamlines. The photocathode laser system offers two parallel outputs, each providing pulses of >100 µJ energy and 11 ps FWHM duration at 1064 nm center wavelength. One output is converted to the deep UV (266 nm) with conversion efficiencies > 25%. The second beam is sent to a laser heater to reduce microbunching instabilities, increasing the SASE efficiency. For efficient XFEL operation several state-of-art laser controls were implemented, such as: feed-forward algorithm to flatten electron charge along the bunch, active beam stabilization with < +/-10 µm beam pointing jitter at the photocathode, state machines for hands-off operation, temporal pulse synchronization and drift compensation. The latter reduces the timing jitter of the electron bunches to less than 45 fs rms.

INTRODUCTION

The high availability requirements of the photocathode injector laser (>8000 hours of 24/7 operation) [1] for the European XFEL merited the installation of a second laser system, based on high-gain Nd:YVO_4 material to act as a “hot swap” backup in case of failure or temporary downtime of the already existing complex chirped pulse amplifier (CPA) Yb:YAG laser system in 2017. This simpler non-CPA Nd:YVO_4 system was designed for producing all required laser parameters for European XFEL operation with exception of an experimental 3 ps “short pulse” mode with high availability and low jitter. After the integration of the Nd:YVO_4 laser into the XFEL injector, its demonstrated robust performance (>99% uptime for 2018) made the Nd:YVO_4 system the primary driving laser for the XFEL. This paper focuses on key technology developments for the injector laser beamline that enable delivery of laser light to the cathode with high reliability and stability.

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THE SYSTEM

Both European XFEL photocathode laser systems offer two outputs, for electron gun (UV) and laser heater (NIR), respectively. Relevant laser parameters are provided in Table 1. The UV and NIR outputs from both lasers are multiplexed; with one laser blocked during normal operation. We also can produce complex bunch trains by simultaneously using both sources. A schematic system overview is provided in Figure 1.

Table 1: Summary of Laser Parameters.

Parameter	**Nd:YVO_4 Laser**	**Yb:YAG Laser**
Oscillator Type	Yb:fiber	Yb:YAG
Amplifier Type	Nd:YVO_4	Yb:YAG
IR Wavelength	1064 nm	1032 nm
UV Wavelength	266 nm	257 nm
Pulse Width (UV)	8 ps	Short pulse: 3 ps Long pulse: 12 ps
Intra burst repetition rate	500 kHz, 1.13 MHz, 2.25 MHz, 4.5 MHz	
Energy (UV)	>5 µJ / pulse	>3 µJ / pulse
Energy (IR)	50 µJ / pulse	

The Nd:YVO_4 system consist of three modules (see Figure 1): a frontend oscillator module, a pulse picking and amplification module, and a frequency conversion module [2].

The oscillator is a saturable absorber-modelocked polarization maintaining (pm) Yb:fiber linear cavity design, dispersion managed and wavelength stabilized by a chirped fiber Bragg grating centered at 1064 nm. The cavity is synchronized to the main RF timing of the European XFEL using slow and fast PZT actuators. Control circuits monitor the oscillator’s mode-locking state, carrier power and noise levels. A fiber-coupled acousto optic modulator (AOM) after the oscillator is used to pick pulses at the user-selected intra burst repetition rate (see Table 1) out of the 54 MHz repetition rate oscillator signal. The picked pulses are then amplified to ~1.2µJ/pulse in cascaded pm-Yb:fiber and Nd:YVO_4 amplifiers.

The picked pulses enter the amplification module, where a second AOM is used to cut out 10 Hz bursts from the pulse train (to generate electron bunches with 10Hz burst repetition rate), to further amplify the pulses in the first Nd:YVO_4 power amplifier to ~8.5µJ.

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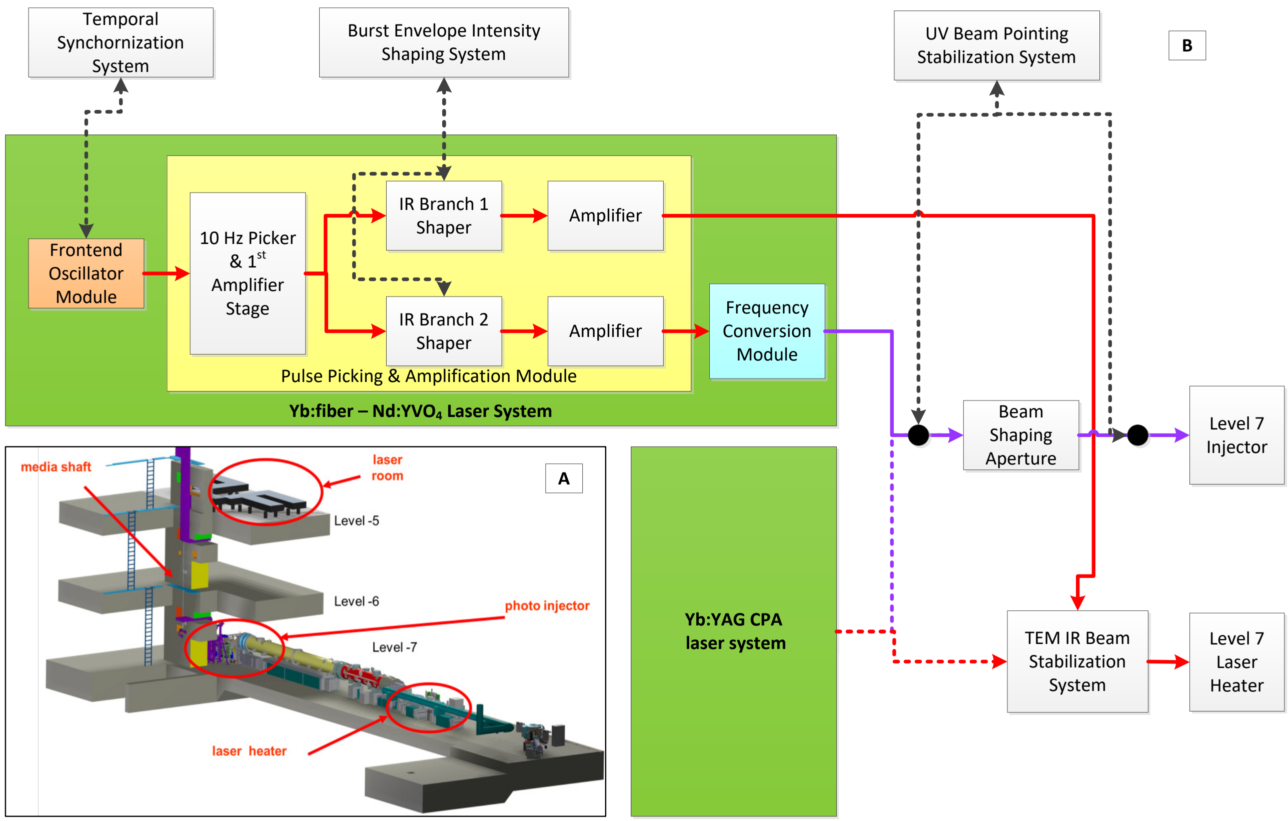

Figure 1A: Injector Building Layout, 1B: Injector Laser System.

The 8.5μJ pulses are split into two parallel arms, additional AOMs shape theburst intensity envelope to a desired profile and a second Nd:YVO_4 power amplifier boosts the pulse energy to the operation point of ~50 μJ / pulse in each arm. All Nd:YVO_4 gain blocks are designed and manufactured by neoLASE GmbH.

One output arm is converted to 266nm via a two-stage second harmonic generation (SHG) process: 1064 → 532nm in 6mm critically phase-matched Lithium Borate (LBO) followed by 532nm → 266nm in 2mm beta Barium Borate (BBO). This process occurs in a purged and sealed, 250x400mm module with motorized linear and rotational stages for remote movement of the nonlinear crystals. Dichronic mirrors are used to filter out remaining 532 nm radiation. The overall 1064 nm → 266 nm conversion efficiency is ~25%.

The UV and NIR beams are then transported from the laser lab in level -5 of the European XFEL injector building to the photo injector & laser heater housed in level -7. The UV beamline consists of multiple beam stabilization stages, variable attenuator, a beam-shaping aperture which cuts the beam profile from a Gaussian to a flat-top beam, shutters controlled by the XFEL Machine Protection System, and shutters controlled by the laser and personnel safety interlock systems.

CHARGE PROFILE SHAPING VIA A FEED-FORWARD ALGORITHM

Electron bunch-to-bunch charge fluctuations are undesirable for XFEL operation. As the burst operation of the injector laser leads to variable inversion efficiency over each pump cycle, and creates a temperature ramp of 100ms within the burst, the intensity of the UV pulses over a burst varies along the burst, despite constant seed pulse energy [3]. A charge feed-forward system is implemented where the electron charge profile over the burst is flattened by controlling the individual pulse intensities after the first main amplifier stage. A FPGA-controlled fast digital to analog (DAC) convertor is used to amplitude-modulate the RF driver of the AOM on the UV branch, which in turn modulates the transparency of the AOM and shapes the intensity profile of the laser pulses over the burst.

A control accuracy of the AOM's diffraction efficiency of better than 0.1% at a maximum diffraction efficiency of 70% has been achieved, with a measured charge stability at the XFEL electron gun of 0.7% rms, (consistent to the measured single pulse stability of 0.6% rms within each laser burst).

TEMPORAL SYNCHRONIZATION

The stability of the arrival time of the laser pulse train at the photocathode is critical for overall FEL synchronization performance. A Phase Locked Loop (PLL)

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type scheme is used to lock the Nd:YVO4 oscillator repetition rate's 25th harmonic (1354 MHz) to the main RF master oscillator running at a RF cavity resonance frequency of 1.3 GHz. In addition, a balanced optical cross-correlation scheme was employed to identify residual timing drifts of the oscillator with respect to an optical reference delivered by a stabilized optical fiber link [4]. The measured drifts are then compensated by acting on the set-point within the oscillator RF synchronization loop resulting in an electron bunch arrival time of 45 fs over 8 hours. (Fig.2)

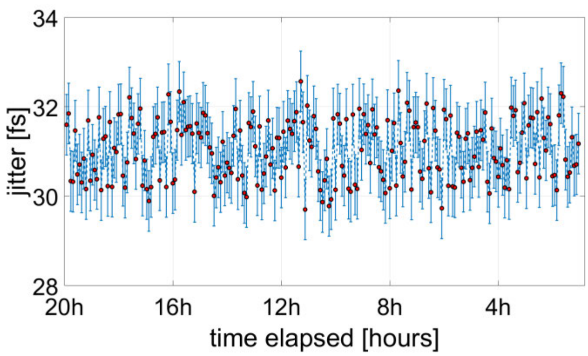

Figure 2: Timing jitter of phase-locked oscillator, mid 2019.

ACTIVE BEAM STABILIZATION

The relay-imaged UV beamline incorporates two active beam pointing stabilization systems at both ends of the beamline. The IR beamline transports a collimated beam and uses a active beam routing and stabilization system.

UV Gun Laser Stabilization

Requirements for the laser spot position on the photocathode are 5% of the beam spot [5], which can vary from 0.1mm to 3mm diameter depending on the aperture settings, with an option to scan the beam over the photocathode. As the laser is relay imaged from the laser room through a non-climate-controlled tunnel shaft in 22m vacuum beam-line, an active beam pointing stabilization system to correct for drifts is essential. The UV wavelength, high robustness, 24/7 uptime and radiation tolerance constrains eliminate most commercial options.

Each stabilization system consists of two actuated mirrors, and two UV cameras in a lead-shielded housing. The image on the cameras is processed (filtered for noise-reduction, binarization, edge-detection and small spot removal) and a first-order moment method is used to determine the centroid, and checks performed to eliminate spurious beam-steering inputs. The mirror-to-camera position transfer matrix was determined during characterization, and is used to drive actuators for a fast-converging steering algorithm. Step-size and error thresholds can be dynamically set to reduce large movements of the beam during the steering process, and to eliminate jerky transitions. The high dynamic range seen by the system during operation (from single bunch operation to bursts consisting of 2700 bunches) requires dynamic changes to the camera exposure and gain settings to prevent saturation and errors in centroid calculation when switching from a high number to a low number of bunches.

IR Laser Heater Stabilization

The IR laser light is collimated in the level -5 laser lab and transported to injector level -7 over a 46 meter beamline to the laser heater. System requirements call for less than 10µm jitter in spot position at the laser heater.

The stabilization system (ALIGNA, TEM Messtechnik) combines an angle and position detector with seven active mirrors forming a feedback loop to suppress thermal drifts and jitter.

Input rms error of ~0.015 mrad results in max 30 µm rms error at the far end without active beam stabilization. With active stabilization, the same input provides max 7.5 µm rms error (see Figure 3).

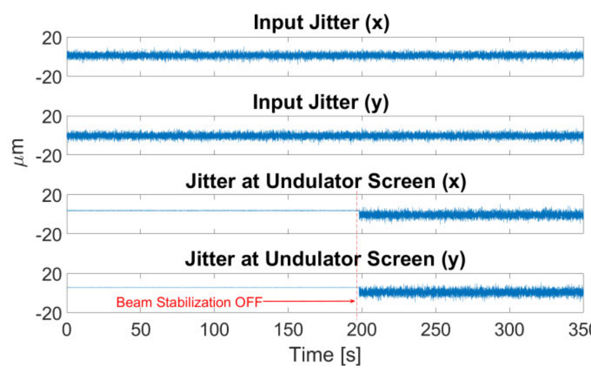

Figure 3: Impact of active stabilization system on laser heater beam.

CONCLUSIONS

We report on a simple and robust hybrid non-CPA Yb:fiber - Nd:YVO_4 laser system, which drives both photocathode and laser heater of the European XFEL facility with 99% availability since 2017. High stability is achieved both by robust design of laser and beam-transport as well as several feedback loops which correct for drifts in pulse energy, timing and pointing. This system is basis for an more complex CPA laser system under current development, which will additionally provide programmable UV pulse durations from 1 – 15 ps FWHM using spectral pulse shaping and larger bandwidth Yb:YAG gain blocks.

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