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HIGHLY-STABLE, HIGH-POWER PICOSECOND LASER OPTICALLY SYNCHRONIZED TO A UV PHOTOCATHODE LASER FOR AN ICS HARD X-RAY GENERATION

K.-H. Hong[1,†], W. S. Graves[††], M. R. Holl, L. E. Malin, C. Zhang, Arizona State University (ASU),
AZ 85281 Tempe, USA
S. Klingebiel, T. Metzger, K. Michel, TRUMPF Scientific Lasers GmbH + Co. KG, 85774,
Munchen-Unterfoehring, Germany
D. Gadonas, L. Hand, K. Neimontas, A. Senin, V. Sinkevicius, MGF SVIESOS KONVERSIJA,
UAB (Light Conversion) LT-10233, Vilnius, Lithuania
[1]also at Massachusetts Institute of Technology (MIT), MA 02139, Cambridge, USA

Abstract

We report on highly stable and optically synchronized laser systems for the Compact X-ray Light Source (CXLS) at ASU which is based on inverse Compton scattering (ICS) of a high brightness electron bunch on a picosecond laser pulse. An ICS driver laser, a thin-disk Yb:YAG amplifier, generates 200 mJ, 1.1 ps pulses at 1 kHz repetition rate with excellent shot-to-shot (0.52% rms) and long-term (0.14% rms of drift over 24 hours) energy stabilities as well as an excellent pointing stability of better than 4 μrad. The M^2 factor is as good as ~1.5, leading to an achievable laser intensity of $>10^{17}$ W/cm^2 with *f*/10 focusing. A high-stable photocathode laser, a frequency-quadrupled Yb:KGW amplifier, is optically synchronized to the ICS laser with a timing jitter of 33 fs rms. The cavity length of a common Yb:KGW laser oscillator is also locked to an RF reference with a timing jitter of 52 fs rms.

INTRODUCTION

The ICS of high-energy electron beams with intense laser pulses enables to generate high-flux hard X-rays in a compact setup [1], compared to traditional large-scale accelerator-based X-ray facilities. Under the CXLS project at ASU we are developing an ICS source with projected flux of about 10^8 photons/shot at the high repetition rate of 1 kHz. This source will eventually serve as a compact X-ray free-electron laser (CXFEL) with electron nano-bunching, via electron diffraction and emittance exchange, being implemented for the fully coherent X-ray generation. The ICS interaction at CXLS facility occurs between a few tens of MeV electron beam, produced at a photo-injector and accelerated by a compact X-band linear accelerator (LINAC), and a tightly focused, high-energy picosecond (ps) infrared (IR) laser pulse with a laser intensity of ~10^{17} W/cm^2. The photo-injector is initially triggered by a sub-ps ultraviolet (UV) photocathode laser. The ultimate performance of an ICS source is critically dependent on the parameters and stability of driver laser pulses, such as: 1) achievable peak intensity, *i.e.*, peak power and beam quality, with reasonable focusing geometry, 2) shot-to-shot and long-term energy stability, 3) beam pointing stability, and 4) relative timing stability to the photocathode laser pulses. To address these issues with the laser sources for ICS, we use the diode-pumped, high-power ultrafast diode-pumped Yb-doped laser amplifier technology that has made a significant advance over the last decade [2–5]. Highly stable UV photocathode laser pulses are also generated using the Yb-doped laser technology and nonlinear frequency conversion.

In this Contribution, we demonstrate a highly stable, 1 kHz, 200 mJ, 1.1 ps, 1030 nm laser with good beam quality as an ICS driver, which is optically synchronized to a UV photocathode laser with a relative timing jitter of 33 fs rms.

CXLS LASER SYSTEMS

The overall schematic of the CXLS facility under construction is shown in Fig. 1. The electron beam is triggered by the UV photocathode laser and then accelerated by an X-band RF electron gun [6] and LINAC (Tibaray LLC). The electron beam is focused into the ICS interaction point (IP) in vacuum and makes a head-on collision with the ICS driver pulse for hard X-ray generation. A 72.6 MHz, 15 nJ mode-locked Yb:KGW laser oscillator seeds both the ICS and photocathode lasers after a beam splitter, which ensures the optical synchronization of two lasers in the first hand. The cavity length of the oscillator is locked to an RF reference (Rhode & Schwarz SMB100A) with a timing jitter of 52 fs integrated over 2 Hz – 600 kHz. This RF locking is critical for stable acceleration of electron beams with the X-band LINAC.

The ICS driver for CXLS is a ultrafast high-power Yb:YAG thin-disk regenerative amplifier (RGA; Dira 200-1, Trumpf Scientific GmbH) and the UV photocathode laser is a sub-mJ frequency-quadrupled, diode-pumped solid-state Yb:KGW RGA (Pharos, Light Conversion), both employing chirped pulse amplification (CPA) technique. The RGA architecture inherently ensures the excellent stability of energy and beam pointing of output pulses.

The ICS laser consists of a chirped fiber Bragg grating (CFBG) stretcher, a fiber pre-amplifier, Yb:YAG thin-disk RGA, and a dielectric-grating pulse compressor. The thin-disk RGA is pumped by two multi-kW diode lasers at 940 nm. Four intracavity mirrors are used for actively stabilizing beam pointing, which significantly improves the

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†kyunghan@mit.edu, †† wsg@asu.edu

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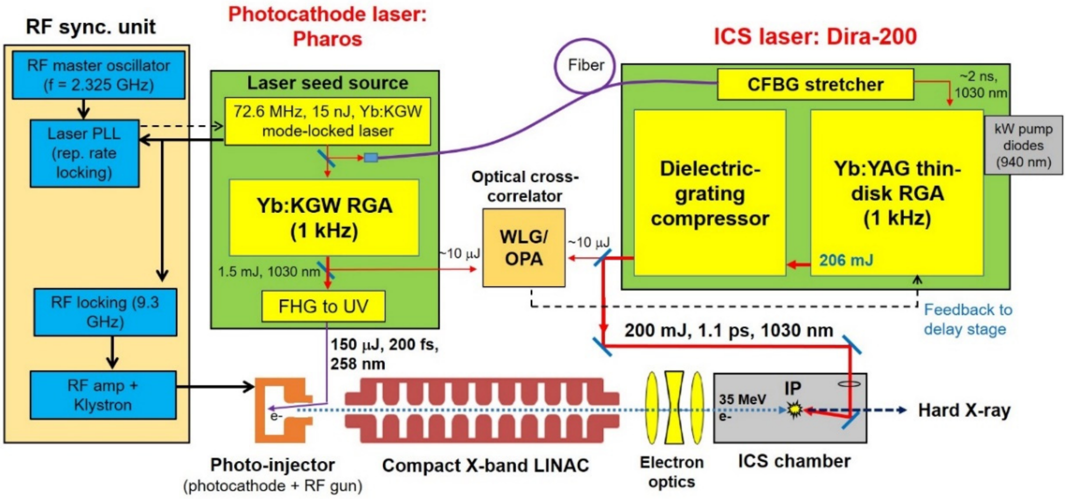

Figure 1: Optical and RF schematics of CXLS facility composed of photocathode laser, ICS laser, photo-injector, X-band LINAC, ICS chamber, and RF synchronization unit. Acronyms are found in the main text.

long-term energy and pointing stabilities as well as shortens the system warm-up time to below 10 minutes. The pump power is also modulated to stabilize the RGA output energy. With the maximum energy from the RGA being set to ~206 mJ we obtain compressed pulse energy of 200 mJ with an excellent compression efficiency of 97%. At full energy operation the shot-to-shot energy stability is 0.52% rms (Fig. 2(a)) and the long-term energy stability over 26 hours (the drift of average power), 0.14% rms (Fig. 2(b)). Beam pointing stability better than 4 µrad rms on both axes is measured after the compressor (Fig. 2(c)). The spectral bandwidth of amplified pulses is 0.72 nm in full width at half-maximum (FWHM) and the autocorrelation (AC) measurement in Fig. 2(d) shows the compressed pulse duration of ~1.1 ps in FWHM at full energy. The pulse pedestal, which is less significant in a low-energy measurement, is attributed to mild self-phase modulation from the output window after the compressor and the air path within the compressor. The M^2 factor is as good as ~1.5 at full energy, leading to achievable laser intensity of $>10^{17}$ W/cm^2 with *f*/10 focusing, which is sufficiently high for driving the ICS interaction.

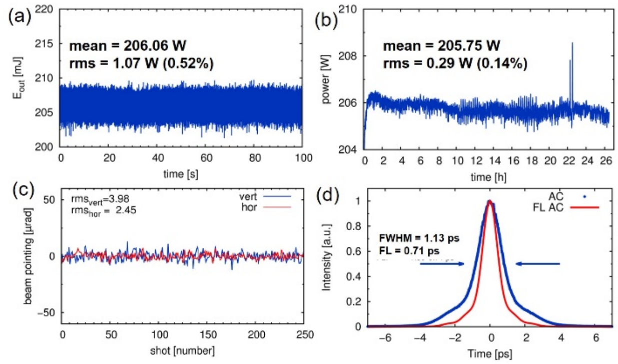

Figure 2: Performance of the ICS laser. (a) Shot-to-shot energy measurement, (b) long-term energy drift, (c) pointing stability measurement, and (d) AC measurement of compressed pulses at full energy. FL, Fourier limit.

The photocathode laser that shares the oscillator with the ICS laser generates 1 kHz, 1.5 mJ, ~200 fs pulses at IR, 1030 nm and 150 µJ, ~200 fs pulses at UV, 258 nm after fourth-harmonic generation (FHG). Fig. 3 shows that the power stability of UV pulses is as good as ~0.15% rms over 14 hours. The ~10 µJ pulse of IR leakage is used for optical timing locking with the Dira laser, as described in next section.

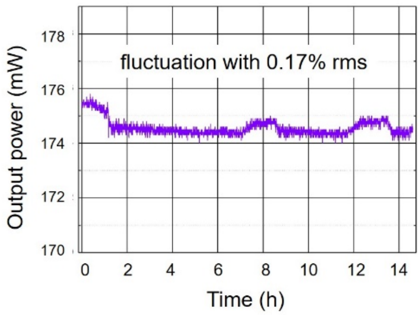

Figure 3: Power stability of UV pulses over 14 hours.

LASER SYNCHRONIZATION

In addition to the basic optical synchronization from a common laser oscillator, optical timing locking between the two lasers is achieved via a feedback loop with an optical cross-correlator [7] based on a single-stage optical parametric amplifier (OPA), where the frequency-doubled pulse (515 nm) from Dira laser is a pump and the Pharos IR pulse serves as a chirped signal pulse in the 800-900 nm wavelength range after going through the white light generation (WLG) in a glass plate and then being dispersed in an additional glass block. The amplified wavelength of OPA registers the relative timing between the pump and signal pulses. Using the wavelength information as a feedback signal to a motorized delay stage in the Dira laser we are able to suppress the timing drift between two pulses. Approximately 1 ps of timing drift is observed over ~5 minutes period (red line in Fig. 4(a)) for the free-running case, but this drift is locked to zero if the feedback loop is turned on (blue line in Fig. 4(b)). With further analysis of phase noise density (Fig. 4(b)) the integrated timing jitter is measured as 33 fs rms with the feedback on (blue line in Fig. 4(c)). Noise spectrum of Fig. 4(b) reveals that mechanical vibration of 20-120 Hz is the main cause of residual jitter. Nevertheless, this jitter corresponds to only 3% of the ICS laser pulse duration. Since the timing jitter between the Pharos IR and UV pulses is negligible, the ICS laser pulse and the UV photocathode laser pulse are tightly synchronized as well.

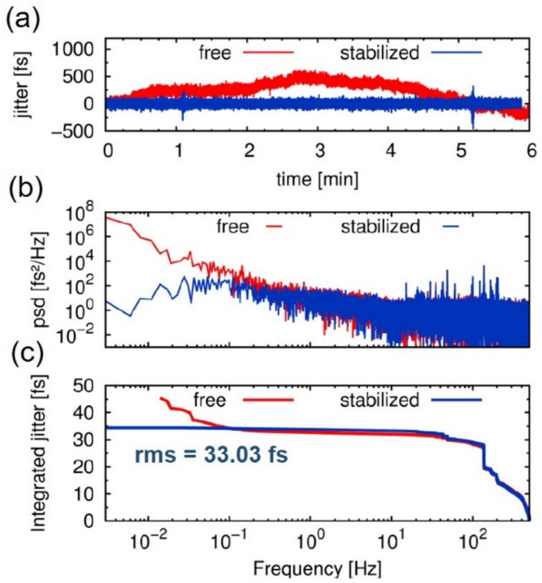

Figure 4: Synchronization of two laser pulses and characterization of relative timing jitter. (a) Relative timing jitter without (red) and with (blue) feedback loop, (b) phase spectral density (PSD) measurements of free-running (red) and stabilized (blue) laser pulses, and (c) integrated timing jitter from (b).

CONCLUSION

We developed a highly-stable, high-intensity laser synchronized to a photocathode laser, which is suitable for ICS experiments. The ASU CXLS facility is currently under commissioning at MIT Bates Lab. Ultimate timing jitter between the electron beam and the ICS laser pulse needs to be characterized after the X-band RF LINAC and ~35 MeV electron beamline are fully installed. More details on the status of ASU CXLS system will be reported elsewhere.

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