PHASE NOISE COMPARISON OF SHORT PULSE LASER SYSTEMS

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Abstract

This paper describes phase noise measurements of several different laser systems that have completely different gain media and configurations including a multi-kW free-electron laser. We will focus on state-of-the-art short pulse lasers, especially drive lasers for photocathode injectors. Phase noise comparison of the FEL drive laser, electron beam and FEL laser output also will be presented.

INTRODUCTION

The stability of the drive laser plays a very important role in the performance of photogun-based accelerators and free-electron lasers (FELs). With the increasing demand for shorter wavelengths (including XFEL) and shorter pulse duration (sub-50 fs), phase noise and timing jitter issues are drawing more and more attention. Over the past decade, short pulse lasers technology has seen dramatic advancement due to the rapid development of solid-state materials and high power semiconductor laser diodes. Some state-of-the-art femtosecond lasers have shown superior performance in terms of both amplitude and phase stability. These lasers provide a unique opportunity to overcome challenges in the development of the next generation accelerator light sources.

The photogun drive laser is used to extract the electron beam that provides the gain medium for numerous FELs worldwide. Drive laser instabilities will limit high power FEL operation. Of all the instabilities associated with short pulse high repetition rate lasers, timing jitter appears to be the most important and most difficult to control. In this paper, we present phase noise and timing jitter measurements of several different lasers that can be used to drive photoguns. We believe a comparison of these lasers provides valuable information about the pros and cons of each system in their specific applications.

METHOD AND SETUP

Phase noise is a drive laser quantity that is often discussed. Phase noise is a direct representation of the timing jitter of a mode-locked laser system. Timing jitter can be quantified by measuring the phase noise. There are two basic methods widely used to measure the phase noise (and timing jitter) of optical pulse trains; a) the Phase Detector Technique (PDT) and, b) the Power Spectral Density Technique (PSDT) [1]. The PSDT provides better precision and was used for all of the measurements described below. The measurement requires a fast photodiode and a spectrum analyzer. In this case the timing jitter of the mode-locked or gain-switched optical pulse train is determined by measuring the phase noise spectral density.

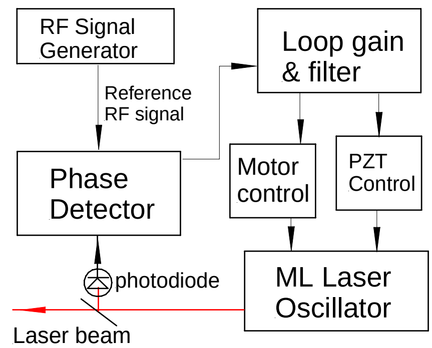


Fig.1. Schematic of a generic phase locking system.

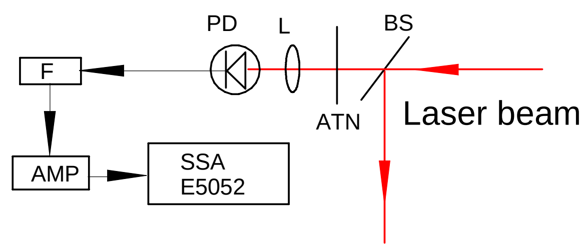


Fig.2. Schematic of the timing jitter measurement setup. BS, beam splitter. ATN, attenuator. L, lens. PD, photo-diode. F, RF filter. AMP, RF amplifier.

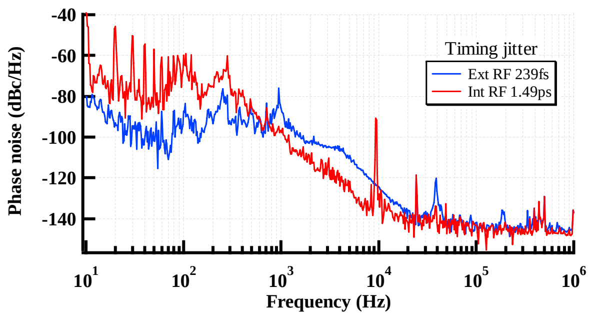
Fig.1 shows the basic principle of a generic phase-locking system used by many lasers. The laser phase error is detected and corrected by the RF feedback loop. The measurement setup is shown in Fig.2. The detectors used in the experiment were fast photo-diodes with bandwidth between 2 to 20 GHz. A Signal Source Analyzer (SSA, Agilent E5052A) was used for the phase noise and timing jitter data acquisition. This instrument presents faster speed and better precision compared with some other spectrum analyzers. The phase noise is usually measured at 1.497 GHz, the 20th harmonic of the 74.85 MHz laser pulse frequency in order to minimize the laser amplitude noise. The 1.497GHz signal was filtered out using an RF filter and amplified by a low noise RF amplifier before being fed into the SSA. For higher repetition rates, it was sometimes difficult to perform the measurement at the 20th harmonic. The noise added to the measurement from the RF amplifiers and filters was determined to be negligible.

DIFFERENT LASER SYSTEMS

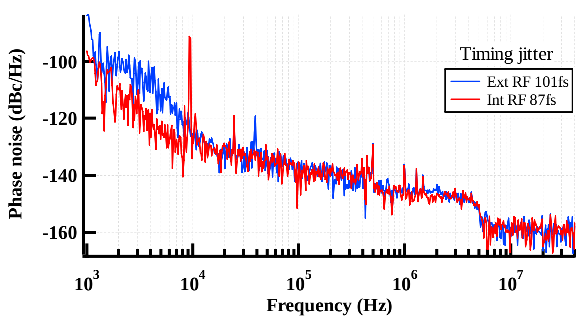
Flash-lamp-pumped Active Mode-locked Laser

The first laser system tested was a frequency doubled CW mode-locked Nd:YLF laser pumped by flash lamps

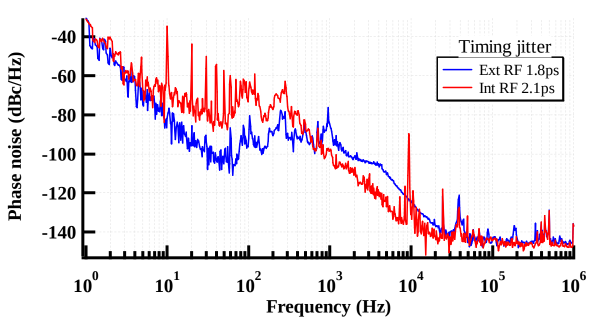
(Coherent Antares laser made in early 90's). It has served as the drive laser for the photocathode injector at the JLab FEL facility for more than ten years. We studied the stability of this laser in the past [2]. Here we will focus on the phase noise characteristics. The laser has a folded cavity design and intracavity acousto-optic modulator (AOM) for mode-locking. The AOM can be driven with RF supplied by the laser power supply (internal RF) or with RF from the accelerator (external RF). The laser phase is monitored and controlled by the RF control module. A fast photodiode detects the optical pulses signal from the infrared light leaking through the high reflector. Unlike most other laser systems that use active laser cavity length adjustment to minimize the phase noise, the RF to the acoustic mode-locker on this laser is tuned to compensate the phase change. To detect the phase error and complete the phase loop, the 20^{th} harmonic of the laser frequency (74.85 MHz) is filtered out, amplified and sent to an RF control module.



(a)



(b)



(c)

Fig.3. Phase noise spectral density plots of flash-lamped pumped Antares Nd:YLF laser at different offset frequency. (a)10 Hz~1 MHz. (b)1 kHz~40 MHz, and (c)1 Hz~1 MHz. As explained in the text, Ext and Int refer to external RF and internal RF, respectively.

From the results shown in Fig.3, the excellent performance is primarily due to the fact that the laser cavity was designed to have a particularly stable length: all components are mounted to an Invar rod to reduce temperature dependence. In addition, the phase control loop associated with the RF reference signal is very important, as can be seen by comparing the two RF sources, internal and external. The laser performs significantly better when using RF supplied by the accelerator, with timing jitter five times less compared to that obtained with RF supplied by the power supply. Most of the phase noise comes from the lower frequency band below a few hundred Hz. There are always more noises below 10Hz and the feedback loop does little to reduce them (Fig.3(c)). Usually a flash-lamp pumped laser tends to have noticeably higher phase noise than those pumped by diodes. But this measurement clearly indicates that the phase noise of a flash-lamp pumped system can be controlled to a very low level.

SESAM Mode-locked Laser

The SESAM mode-locked $Nd:YVO_4$ laser serves as the master oscillator, providing seed pulses for a multi-stage amplifier that provides over 50 W average power at 1.064 um and 25 W at 532 nm. This Maser-Oscillator-Power-Amplifier (MOPA) system will be used to drive a 100mA photoinjector. A detailed system description can be found in another paper [3]. The passively mode-locked $Nd:YVO_4$ laser is diode-pumped and produces over 500 mW at 1064 nm with 74.85 MHz pulse repetition rate and 25 ps pulses (Time-Bandwidth Product, GE100). It uses a semiconductor saturable-absorber mirror (SESAM) to initiate mode-locking. The laser cavity length is actively stabilized and the phase of the optical pulse train can be locked to an external RF reference signal.

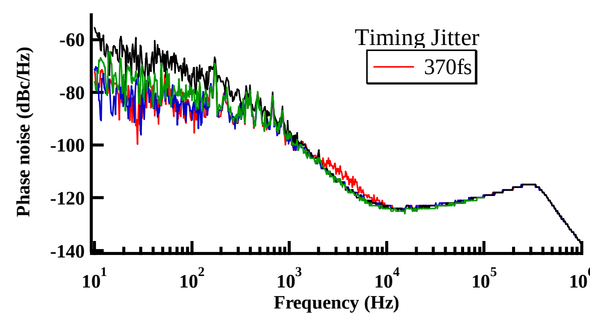


Fig.4. GE100 laser phase noise spectral density plots obtained over few minute time period. Mostly, the timing jitter is less than 400 fs but occasionally larger values are obtained.

When the laser cavity is optimized, it runs very well with timing jitter around 300 fs. Random fluctuations can be seen from time to time, which may be caused by environmental disturbances. Phase noise spectral density plots for this laser are shown in Figure 4. These plots were obtained over a few minutes and mostly timing jitter is less than 400 fs but occasionally values surge over 500fs. We also intentionally unlocked the cavity length feedback loop. This has a profound affect, with timing jitter increasing to 4 ps (Fig.5). The overall timing jitter also depends highly on the laser cavity alignment and optimization. Timing jitter values can exceed 1ps in the case of poorly aligned cavity.

Phase noise measurements were also made downstream of the power amplifier section of this laser system. The Master oscillator (MO) seed light from the passively mode-locked Nd:YVO_4 laser passes through four Nd:YVO_4 amplifiers, with total output power at 1.064 um greater than 50 W. As expected, the diode-pumped amplifiers do not add much noise to the system (Fig.6). The added noises are most likely from the environment.

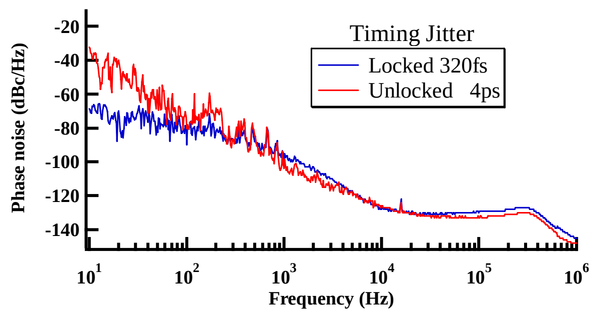


Fig.5. GE100 laser phase noise spectral density plots with laser cavity length feedback loop open and closed.

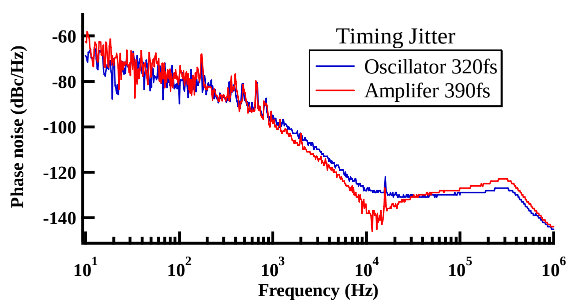


Fig.6. MOPA laser: GE100 laser and multistage power amplifier. Phase noise spectral density plots comparing MO and MOPA signals.

KLM Ti:sapphire Laser

Widely used fs-pulse Ti:sapphire lasers rely on self-mode-locking (KLM), a passive technique that relies on Kerr lensing within the Ti-sapphire crystal and a gain aperture effect that provides more gain for shorter pulses. These lasers are broadly tunable and can generate extremely short pulses because of the exceptionally broad gain bandwidth of the lasing medium.

Phase noise measurements were carried out using a Spectra Physics Kerr mode-locked Ti:sapphire laser (Tsunami, 100fs, 1W at 800nm) pumped by a frequency-doubled and diode pumped Nd:YVO_4 laser (Millennia, CW 10 W at 532 nm). The laser has a phase-locking unit that detects and corrects the laser phase by adjusting the cavity length with a pico-motor and PZT attached to the high reflector (HR) end mirror. A photodiode picks up the laser signal from a beam splitter and the phase is compared to the reference RF to create a phase error signal. The pulse repetition rate is 74.85 MHz, the same as for measurements with other laser systems. Phase noise spectral density plots are shown in Fig.7 for measurements at two different times. As with the SESAM mode-locked laser, phase noise was closely related to cavity alignment and optimization. The timing jitter was observed to jump up and down, but mostly values stay within a range between 200 and 400 fs (Fig. 8). When the feedback loop was turned OFF, timing jitter values surge upward by a factor of ten.

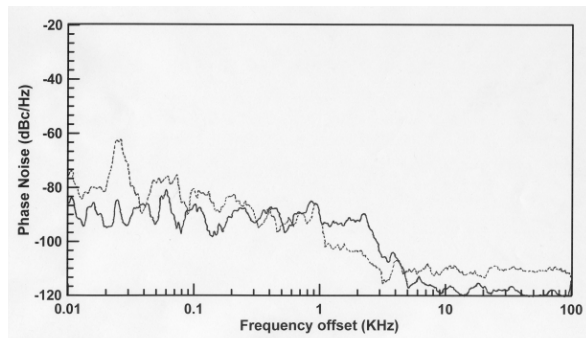


Fig.7. Tsunami laser phase noise spectral density plots at two different times.

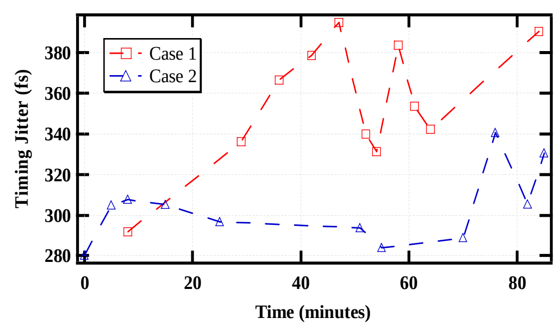


Fig.8. Tsunami laser. Timing jitter versus time. The square and the triangle stand for the data taken at two separate times.

The Tsunami laser uses an intracavity AOM to initiate and stabilize mode-locking. We investigated the influence of the AOM on timing jitter by making phase noise measurements with the AOM on and off. Measurements indicate that the AOM does not introduce additional instability. This confirms that AOM only helps to start the KLM process and set the fundamental frequency for the feedback loop to lock the cavity length. Once the cavity is optimized and loop is closed, AOM is not needed.

Gain-switched Diode Laser

Gain-switched diode lasers have a number of advantages over mode-locked lasers such as simplicity, good stability and low cost. They also provide a wide range of pulse repetition rates independent of laser cavity length. While there is no doubt about amplitude stability, we did an investigation of phase noise performance. The laser system consists of a sub-milli-watt gain-switched InGaAs laser at 1.56 um and a fiber amplifier to boost the power to a level suitable for the measurement. Gain-switching at frequencies below 100 MHz produces longer optical pulses with tails, so a step-recovery diode (SRD) was used to improve the temporal profiles of the laser pulses. There is no cavity length adjustment for this system.

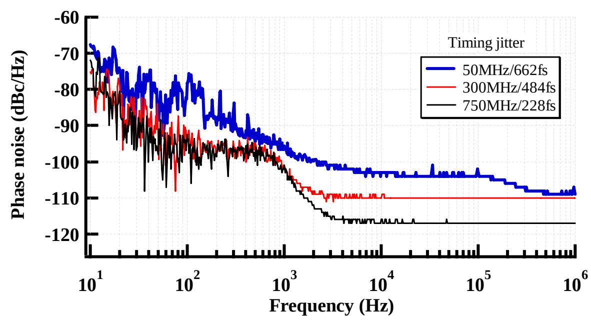


Fig.9. Phase noise spectral density plot and timing jitters of gain-switched diode laser and fiber amplifier at three different repetition rates.

Phase noise spectral density plots for the gain-switched diode laser at three pulse repetition rates are shown in Figure 9. The timing jitter increases inversely with the pulse frequency. At the lowest frequency 50 MHz, the timing jitter is larger than lasers mentioned previously. Note for the 50 MHz case, the phase noise at frequencies > 1 kHz is noticeably higher. The RF generator used here is the same as the previous lasers. The possible contribution to the noise is poor impedance matching at the SRD and driving circuits. The signal from the SRD shows different waveforms as the RF frequency and power changes. It requires a good balance between these parameters including the near threshold DC bias. Further work is needed to improve the performance before they can be adapted into the FELs.

High Power FEL

So far we have only talked about lasers with cavity lengths of 1.5 m or shorter. We also studied the phase noise properties of the high power JLab FEL, with output power over 1kW (pulse-width about 200 fs and wavelength 1.6 um). The FEL laser cavity is composed of two mirrors separated by 32 m. The mirrors sit inside vacuum chambers: the laser cavity length can be tuned over 1 cm with resolution sub-micron but there is no active cavity length control.

Phase noise measurements were made under different FEL operating conditions. Results are presented in Fig.10, together with the noise spectrum of the Antares drive laser. The FEL timing jitter is on the same level as other lasers, even operating without cavity length stabilization. The phase noise rises dramatically at all off-set frequencies, especially at the higher bands. If we look at the electron bunches in the wiggler region, they actually appear to be very quiet (timing jitter less than 60 fs). The phase noise actually gets suppressed compared to the drive laser. The two curves in Fig.10 for FEL were taken at two different times to show the random fluctuation during the same machine operation. In view of the exceptionally long FEL laser cavity length, the FEL output is remarkably stable. However, this measurement suggests that the FEL phase noise could be reduced using feedback mentioned in earlier sections.

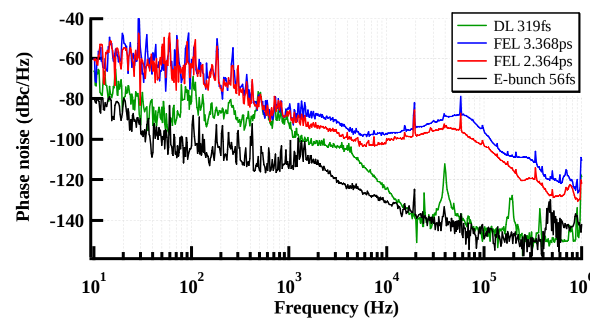


Fig.10. FEL phase noise spectra. The carrier frequency is 1.49 GHz. Laser frequency is 9.37 MHz. Lasing wavelength is 1.6 um. DL, drive laser. E-bunch, electron bunches.

SUMMARY

We have presented the phase noise characteristics of several lasers that can be used to drive GaAs photoguns. The performance of each laser depends on the phase locking mechanism. Active cavity length adjustment remarkably reduces the phase noise. The overall phase noise appears unrelated to the optical pulse length. The flash-lamp-pumped system does not necessarily have to be noisier. Diode-pumped amplifiers present very minor noise addition to the seed pulse. The gain-switched laser is good for repetition rates over 100 MHz but needs improvement to be used at sub-hundred MHz band.

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