BEAM JITTER SPECTRA MEASUREMENTS OF THE APEX PHOTOINJECTOR*

H. Qian#, J. Byrd, L. Doolittle, Q. Du, D. Filippetto, G. Huang, F. Sannibale, R. Wells, J. Yang,
LBNL, Berkeley, CA 94720, USA

Abstract

High repetition rate photoinjectors, such as APEX at LBNL, are one of the enabling technologies for the next generation MHz class XFELs. Due to the higher repetition rate, a wider bandwidth is available for feedback systems to achieve ultra-stable machine and beam performance. In a first step to improve APEX beam stability, the noise spectra of the APEX laser beam and electron beam are characterized in terms of amplitude and timing. Related feedback systems are also discussed.

INTRODUCTION

The Advanced Photo-injector Experiment (APEX) is for demonstration of MHz repetition rate high brightness electron beam injection for the next generation high repetition rate free electron lasers [1]. APEX is staged in 3 phases. In phase 0, the 186 MHz normal conducting (NC) RF gun was successfully conditioned to achieve CW operation at nominal beam energy (750 keV) with low vacuum pressure performance (10^{-11} – 10^{-9} Torr). In phase I, several high QE photocathodes are being tested to demonstrate 0.3 mA beam current, and 6D beam phase space will be characterized at gun energy. In phase II, beam brightness will be more reliably demonstrated after being compressed by a buncher and accelerated by a 30 MeV NC pulsed linac.

Due to CW RF operation and MHz beam rep. rate, a wider bandwidth (BW) is available for feedback system, so ultrastable operation of the next generation FELs is being pursued [2]. Since photoinjector is one of the main noise sources, a tighter stability requirement has been put on photoinjectors like APEX, as shown in Table 1. With Phase I installed and in operation, efforts to characterize and improve APEX RF, laser and electron beam stability have been initiated.

Table 1: LCLS-II Injector Stability Requirements [3]

Injector Stability Parameters	RMS Tolerance
Bunch charge	1%
Timing jitter at injector exit	25 *fs*
Electron beam energy	0.01%
$\Delta x/\sigma_x$ and $\Delta y/\sigma_y$	1%

GUN RF STABILITY

Compared with the high frequency NC RF guns, APEX gun is special in terms of RF dependence of electron beam stability. Due to a low resonant frequency of 186 MHz, 1 degree of RF phase corresponds to 15 ps, which makes the electron beam energy much less sensitive to laser-RF timing jitter. Due to relatively low energy of 750 keV and inverse square dependence of drift space R_{56} on beam energy, beam arrival jitter before the linac booster becomes much more sensitive to RF amplitude jitter. In this sense, APEX gun behaves more like a DC gun.

In order to achieve the 25 *fs* arrival jitter at injector exit, the gun RF amplitude jitter is at least 7×10^{-5} rms without considering other jitter sources. Two feedbacks are implemented on the APEX gun RF, one is a slow feedback based on the cavity frequency tuner to keep the gun frequency on tune, and the other is a fast feedback based on the low level RF (LLRF) drive to keep the gun RF amplitude and phase stable [4]. A close-loop measurement shows gun RF amplitude and phase jitters are reduced to 2×10^{-4} and 0.01 degree respectively, as shown in Fig. 1, and gun dark current energy jitter measurement shows consistent result. The closed-loop amplitude stability of 2×10^{-4} includes strong components from a few lines at 6667 Hz, 6690 Hz, and 9672 Hz, which are out of the feedback BW. These lines show up in forward power and cavity pickup measurements, open and closed loop. Work is ongoing to identify and then eliminate the source of these lines in order to get below 10^{-4} RF amplitude stability.

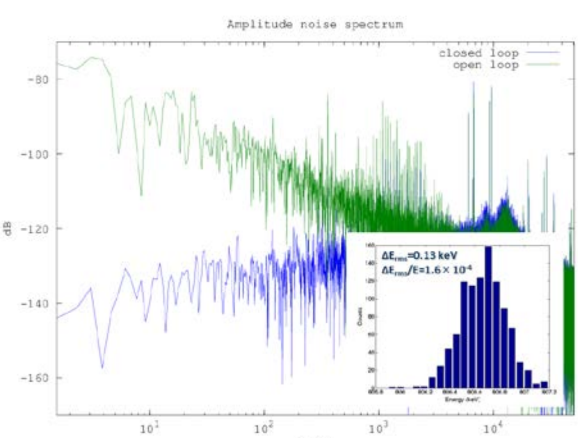

Figure 1: Gun RF amplitude jitter open and close loop (2×10^{-4}), insert shows consistent dark current energy jitter.

*This work was supported by the Director of the Office of Science of the US Department of Energy under Contract no. DEAC02-05CH11231
#hqian@lbl.gov

Copyright © 2014 CC-BY-3.0 and by the respective authors

LASER STABILITY

APEX phase I started with a homemade ~1 W 1MHz Yb doped fiber laser sitting in air without environment regulations [5]. In order to improve the laser stability, a laser enclosure with AC control was built and in operation recently. Besides, a commercial ~1.7 W 1 MHz fiber laser from CALMAR is under commissioning to replace the homemade fiber laser. In the following, both the old and new fiber laser stability will be presented.

Laser Energy Jitter

The long term stability of the old homemade laser has shown 100% fluctuation between day and night due to peak to peak (p-p) temperature fluctuations of ~4 degree C [6]. After installation of the AC enclosure, the p-p temperature fluctuation has dropped to ~1 degree C. A slow feedback based on a motorized continuous neutral density filter to stabilize either laser energy (laser power meter) or beam current (ICT) was also implemented, and close-loop long term stability has shown significant improvement from both the laser and beam performance (~2%) [7, 8]. The long term stability of the commercial laser is expected to be better.

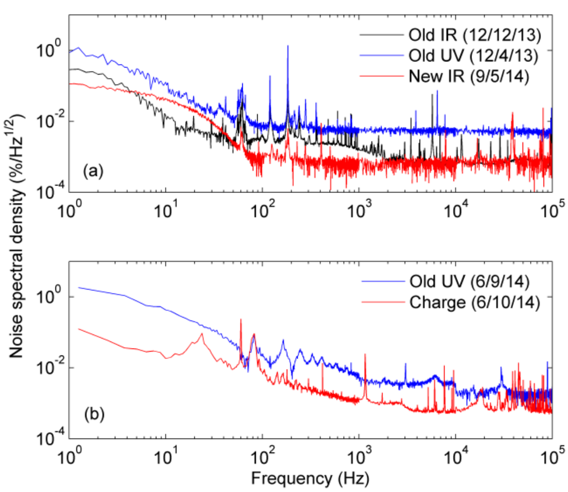

Figure 2: Noise spectral density of (a) APEX laser energy and (b) beam charge at 0.3 mA operation.

Fast feedback based on Pockels cell to reduce fast laser energy jitter was also developed elsewhere, which is effective but sacrifice half the IR energy and downstream harmonic generation efficiencies [9]. To decide whether such a fast feedback is necessary for APEX, the fast noise spectra of the laser energy are measured at DC band of the photodiode signal by a 100 kHz FFT analyser. The DC value of the photodiode signal is ~3 mV, and two photodiode signals of the same laser are used to do cross correlation in order to remove part of the noise induced by photodiode or FFT analyzer. Our measurements show, cross correlations reduce the measured noise below ~100 Hz by ~ 30% compared with no cross correlation.

Energy jitter of both the old laser and new laser are measured as shown in Fig. 2 (a), and integrated noise of old IR, old UV and new IR between 1 Hz and 100 kHz are shown in Table 2. The noise spectra of the three lasers share some common features, such as high noise below 100 Hz, 60 Hz and its harmonic peaks, and high noise above 10 kHz, probably due to pump laser noise. Compared with the homemade laser, the commercial laser is much cleaner below 10 kHz, and integrated noise is reduced by ~60%; the new laser is a bit noisier between 10 kHz and 100 kHz, and two dominating peaks at 38.9 kHz and 80.6 kHz contribute 0.54%, which are out of the BW of even a fast feedback [9]. Understanding and then eliminating the two peaks are very important to further reduce the fast noise of the new laser.

Table 2: UV Energy and Charge Jitter

Frequency (Hz)	Old IR (12/12/13)	New IR (9/5/14)	Old UV (6/9/14)	Charge (6/10/14)
$10^5 \sim 10^4$	0.41%	0.61%	0.68%	0.45%
$10^4 \sim 10^3$	0.26%	0.07%	0.39%	0.13%
$10^3 \sim 10^2$	0.35%	0.03%	0.43%	0.07%
$10^2 \sim 10^1$	0.08%	0.11%	1.2%	0.42%
$10^1 \sim 10^0$	0.36%	0.21%	3.1%	0.17%
$10^5 \sim 10^0$	0.70%	0.66%	3.4%	0.66%

Laser Timing Jitter

Even with a perfect gun and linac RF, the APEX laser timing jitter has to be below 100 *fs* in order to beat the 25 *fs* arrival jitter spec at injector exit. The APEX laser oscillator repetition rate (37.14 MHz) corresponds to the 5th subharmonic of the gun RF frequency, so 5th harmonic of the laser oscillator signal detected by photodiode is locked to the LLRF reference. Two phase lock loops have been implemented, one is a slow piezo actuator, and the other is a fast piezo actuator, both controlling the same end mirror of the laser cavity. Taking the gun RF phase feedback as an example, even with a good feedback, laser phase noise is expected to be limited by ~0.01 degree at 186 MHz, which corresponds to ~150 *fs* and cannot meet the 100 *fs* spec. When the 1.3 GHz LLRF board is built for the downstream linac, the 35th harmonic of the oscillator signal can be used to solve the problem.

In reality, the phase noise of the APEX laser oscillator is much worse than the gun RF phase noise. Before the AC installation, an in-loop timing jitter of ~3 ps has been measured for the homemade laser with the FPGA based LLRF board, and the big timing jitter was attributed to a bad design of the oscillator piezo mount stage. Its transfer function was measured with a piezo actuator step excitation, as shown in Fig. 3, which reveals a lot of dominating mechanical resonance peaks in the mounting stage. To avoid feedback instabilities, the feedback gain coefficients have to be kept low which limit the feedback effectiveness.

Copyright © 2014 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-141-0

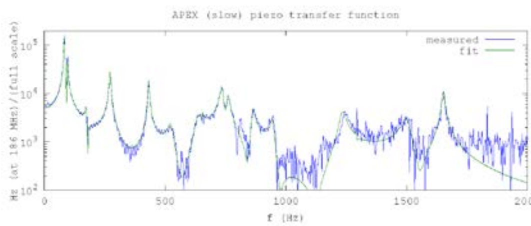

Figure 3: Transfer function of APEX old laser oscillator slow piezo.

After the AC enclosure was installed, the old laser oscillator was relocated and showed much worse phase noise. Signal Source Analyzer is used to measure the absolute phase noise, and a homemade mixer based analog phase detector combined with the FFT analyzer is used to measure relative phase noise between the 5th harmonic of laser signal and LLRF ~186 MHz drive signal. Both SSA and phase detector show a laser timing jitter of ~60 ps from 10 Hz to 100 kHz, and ~6 ps from 1 kHz to 100 kHz, see Fig.4 (a). Similar peaks show up in the laser phase noise spectra as in the laser slow piezo transfer function, such as 82.5 Hz, 92.5 Hz, 420 Hz and so on. The reason why the old laser phase noise is getting much worse after relocation both at the low frequency end and high frequency end is still not well understood.

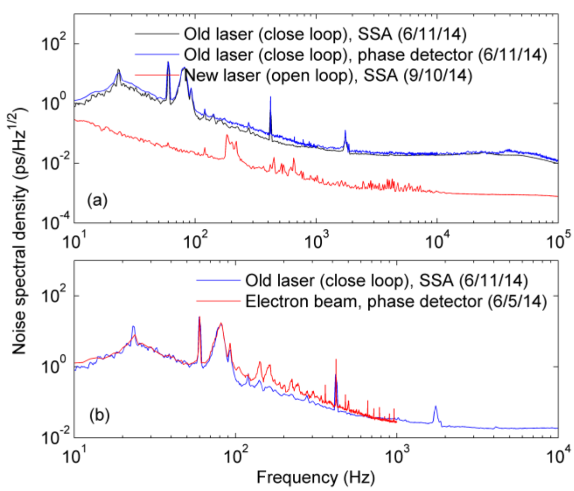

Figure 4: Noise spectral density of (a) APEX laser timing and (b) electron bunch arrival timing.

The new CALMAR fiber laser was installed and is now under test. A new piezo voltage amplifier is being purchased in order to measure its transfer function and lock the new laser to the LLRF reference. The absolute phase noise of the new laser in open loop is measured by SSA, and is already much better than the old laser, as shown in Fig. 4 (a). Integrated timing jitter between 10 Hz and 1 kHz is 0.9 ps, which is expected to be taken care of after phase locking, and timing jitter between 1 kHz and 1 MHz is ~0.44 ps, which is distributed, and becomes the limitation to achieve the 25 *f*s jitter at APEX injector exit. Work is still ongoing to understand this high frequency noise.

ELECTRON BEAM STABILITY

With the homemade phase detector, the 190th harmonic of the APEX BPM (at gun exit) sum signal mixed with the ~186 MHz LLRF drive is used to measure the bunch charge jitter when two signals are in phase, and arrival timing jitter when in quadrature. The main issue with the measurement is that the band-passed BPM signal is relatively low even with the 0.3 mA average beam current, and its signal to noise ratio (SNR) is ~60 dB when considering only thermal noise in the 100 kHz BW, which limits amplitude and timing jitter resolution to be ~0.1% and ~0.9 ps. This resolution is enough to characterize the current electron beam jitter, but becomes difficult for beam arrival jitter when new laser is used.

Fig. 2 (b) and Fig. 4 (b) show preliminary electron beam jitter when running with the old laser system. The beam arrival jitter at the BPM location is ~55 ps between 10 Hz and 1 kHz, whose noise spectra follow exactly the laser phase noise. With the new laser on line, the beam arrival jitter is expected to reduce below ps at gun exit.

The beam charge jitter is surprisingly smaller than the UV energy jitter (Fig. 2 (b)), and their noise spectrum shapes look very different. The charge noise spectrum shows a pronounced peak at 24 Hz which is not seen in the laser energy curve, but a feature of the beam arrival jitter and laser timing jitter curve (see Fig. 4). Based on that peak, it's evaluated that the BPM signal and the LO signal at the mixer are not exactly in phase when measuring charge jitter, but are ~4 degrees off, so part of the phase noise is coupled into the charge jitter curve, which means the real charge jitter could be even smaller than 0.66% between 1 Hz and 100 kHz. One possibility is that 300 pC photoemission is already at the space charge saturation region with current laser beam size, so that charge jitter is not sensitive to laser energy jitter, which is to be tested by measuring the QE curve near 300 pC.

CONCLUSION

Various feedbacks and tools have been developed to measure and improve APEX photoinjector stability. Preliminary efforts on gun RF stability have shown one order of magnitude improvement, and new commercial laser and related feedbacks are under commissioning to further reduce the electron beam jitter.

REFERENCES

[1] F. Sannibale et al., Phys. Rev. ST Accel. Beams 15 (2012) 103501.
[2] J. Byrd, TUOANO01, FEL'13.
[3] T. Raubenheimer, "LCLS-II SCRF Injector System Physics Requirement Document" (2014).
[4] G. Huang et al., Proceedings of IPAC'12, page 3488.
[5] J. Feng et al., Proceedings of IPAC'12, page 2537.
[6] F. Sannibale et al., Proceedings of NAPAC'13, page 709.
[7] D. Filippetto et al., Proceedings of FEL'13, page 255.
[8] F. Sannibale et al., Proceedings of IPAC'14, page 727.
[9] F. Loehl et al., Proceedings of IPAC'11, page 523.

Copyright © 2014 CC-BY-3.0 and by the respective authors