



tions [7]. Series performance tests were carried out to evaluate the performance of the system.

*LLRF Systems Mutual Monitoring and Detecting Experiments*

The LLRF system itself is evaluated before been added on the high power microwave system. The phase jitter control accuracy of LLRF subsystem itself is approximately 50fs, but the pulse RF signal cannot be measured by Signal Source Analyser. Therefore, a mutual monitoring and detecting between two LLRF subsystems method is proposed where an independent LLRF system is applied to measure the other one, which will be a convenient, transportable and portable method to evaluate the deployed LLRF system.

As shown in the figure 2, the LLRF chassis 1 and Sync-Head chassis 1 is the working system which will have been deployed in TTX and run at the close loop mode. The LLRF chassis 2 and Sync-Head chassis 2, which is connected with short cables and been set near the Sync-Head chassis 1, is the monitoring system to estimate the performance of the working system. The reference signals of the two LLRF system are from the same PRDS.

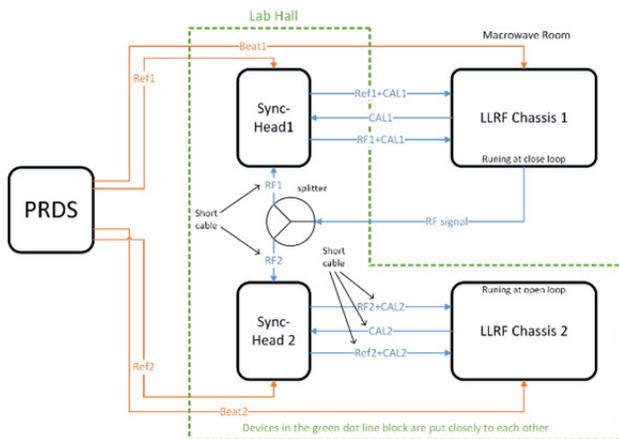


Figure 2: Mutual monitoring and detecting of two LLRF systems.

In the 24-hour long term test, the high power microwave system (SSA and modulator) is not added into the control loop. The test result is showed in fig 3.a, the phase error of working system run at the close loop mode and the phase error is 45.5 fs RMS. By taking the arithmetic mean of subsequence of 100 terms, the moving average(MA) is used to smooth out the drift of the phase error by filtering out the jitter “noise” from random phase error fluctuations. As the blue line shows, the drift of the detecting LLRF system is 4.5 fs RMS, which is suppressed to a very low level; after the removal of the drift, we can get the jitter noise is 45.3fs RMS after the removal of the drift, which is the width of the red line and represents the system hardware noise that cannot be reduced by the close loop correction algorithm.

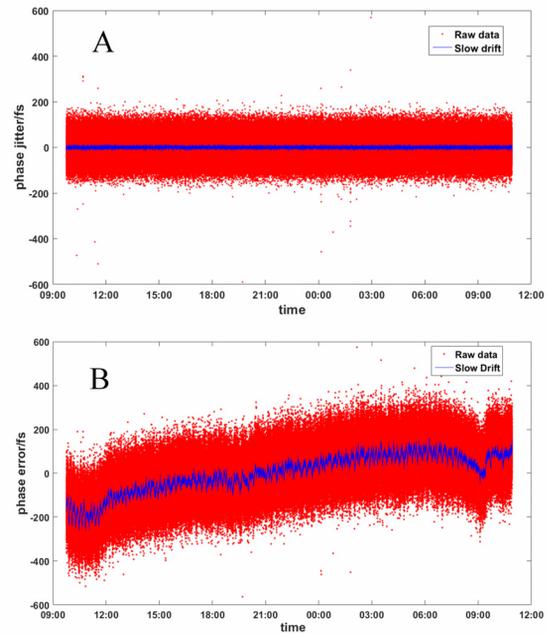


Figure 3: The test result of the 24-hour mutual monitoring and detecting of the two LLRF systems: (a)the phase error that detected by working system itself(b); the working system phase error that detected by the monitoring system.

The working system phase error that detected by the monitoring system is 112 fs RMS, as shown in the figure 3.b, the drift error is 84.3 fs RMS, and the jitter noise is 73.5fs RMS after the removal of the drift. The phase error that detected by the monitoring system is the sum of the two independent systems, hence the real phase jitter of the LLRF system 2 should be  $73.5/\sqrt{2} = 52.0$  fs RMS which is almost equal to that of working LLRF system (45.3 fs). The phase drift error is mainly caused by the environment temperature drift. Since the LLRF system2 is run at open loop as a monitor, its phase drift error (the blue line) is much larger than that of close loop working system.

The mutual monitoring and detecting experiments can also be applied to the laser-RF synchronization. However, the RF signal that gets from the photodiode is continuous wave, it can be measured conveniently by the Signal Source Analyser. Receiver chassis and Sync-Head chassis is quite near and both been put in the constant temperature and humidity room with PRDS, the temperature drift is limited and the Signal Source Analyser can adequately take the system performance assessment, which will be shown later.

*The Test Results of the PRDS System Combined with LLRF & Laser-RF sSystem*

Since the PRDS subsystem is combined with the LLRF or laser-RF synchronization subsystems after the deployment of the whole system, we evaluate the PRDS with LLRF or laser-RF system together instead of the PRDS system separately.

The LLRF system jitter is the sum of the phase jitters from different parts of the LLRF system such as the closed-loop noise of the LLRF chassis itself, the solid state amplifier (SSA) and the high voltage modulator. Supposing they are independent of each other, we can obtain the impact of noise of each section by separately test. We can yield 46 fs RMS phase jitter under close loop of the LLRF Sync-Head and Receiver chassis self-test by careful circuit optimization. Under the same measurement method, the phase jitter test result of the LLRF Sync-Head and Receiver chassis plus SSA is 62 fs RMS. Hence, the impact of the SSA can be calculated by  $\sqrt{62^2 - 46^2} = 41$  fs RMS. The test of the whole LLRF chassis plus high power system (SSA, modulator and klystron) result shows that the signal RMS jitter is 240 fs. Similarly, it can be calculated that the noise from the high-voltage modulator and klystron is  $\sqrt{240^2 - 62^2} = 232$  fs. Hence, the solid-state amplifier and high-voltage modulator are considered to upgrade in the future in order to achieve better performance of the LLRF system.

Before the Laser-RF synchronization system is applied on the real oscillator, a laser oscillator emulator has been made for control loop evaluation, and the final laser oscillator close phase noise is 48.2fs RMS (10Hz-100kHz) with the emulator. The laser oscillator emulator test proved that the phase locking algorithm of Laser-RF synchronization can work properly[8]. After the deployment of the Laser-RF synchronization system, the working performance on the real laser oscillator is measured with the E5052B Signal Source Analyzer. We measured the RF signal that is coupled from the photodiode in the Sync-Head chassis. As showed in figure 4, the absolute integral phase noise of the signal is 83.2 fs RMS (10 Hz ~ 100 kHz) in the closed-loop mode, and the open-loop mode laser oscillator integrated dozens picoseconds phase noise RMS.

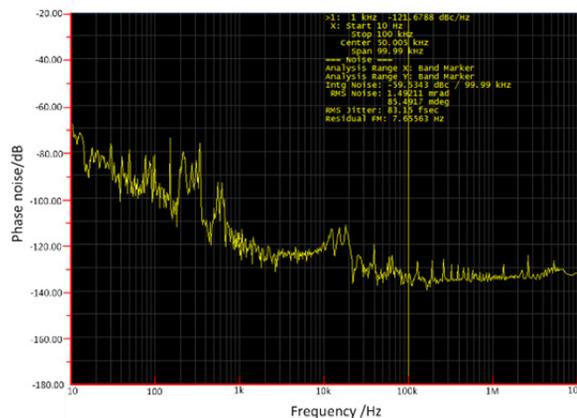


Figure 4: Laser-RF synchronization result by Agilent E5052B Signal Source Analyzer.

The feedback loop bandwidth is tens kHz and it gets out of work if the optical oscillator has a lot of noise above 100 kHz. And there is a crest near 10-20 kHz in the noise spectrum of the closed loop laser oscillator, which is limited by the bandwidth of the PZT and the high-voltage amplifier. Hence, it is required that the laser oscillator

itself have few high-frequency noise in order to achieve high-precision phase-locked. The circuit will be improved in the subsequent revision.

## CONCLUSION

The integrated high-precision timing and synchronization system is realized in TTX, which includes the CW laser based phase reference distribution system, LLRF system and laser-microwave synchronization. And it has achieved a good accuracy of reference signal distribution, LLRF control, laser-RF phase-locking. The phase jitter under close loop of the LLRF system with PRDS is nearly 46 fs RMS for 24-hour test. The digital phase detector is applied to do the phase measurement in the laser-RF synchronization and both fundamental and harmonic signals are used to achieve high precision of the system. And the absolute integral phase jitter of laser-RF synchronization system with PRDS is 83.2 fs RMS (10 Hz~100 kHz) by Agilent E5052B Signal Source Analyzer.

After the system deployment in TTX, the main sources of the phase error noise of the subsystems is measured carefully and analyzed clearly, which will be beneficial for the future system upgrade. A LLRF subsystems mutual monitoring and detecting test is proposed and applied on the deployed LLRF system, which is convenient and efficient to evaluate the subsystem.

## ACKNOWLEDGEMENT

The author thanks Dan Zhang, Zhichao Sun and all the other colleagues from HZCY company for their help in chassis manufacturing, debugging and the assistance in the experiment.

## REFERENCES

- [1] Li R, Huang W, Du Y, *et al.* "Note: Single-shot continuously time-resolved MeV ultrafast electron diffraction[J]". *Review of Scientific Instruments*.
- [2] Yu L, Ben-Zvi I., "High-gain harmonic generation of soft X-rays with the "fresh bunch" technique[J]". *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.*, vol. 393(1), pp. 96-99, 1997.
- [3] Yang J, Huang W, Xu Y, *et al.*, "Synchronization System for Tsinghua Thomson Scattering X-ray Source[C]", in *Proc. IPAC'16*, Busan, Korea, 2016.
- [4] Wilcox R, Byrd J M, Doolittle L, *et al.*, "Stable transmission of radio frequency signals on fiber links using interferometric delay sensing[J]", *Optics Letters*, vol. 34(20), pp. 3050-3052, 2009.
- [5] Huang G, Doolittle L R, Staples J W, *et al.*, "Signal processing for high precision phase measurements[C]", New Mexico, US, 2010.
- [6] L. Doolittle, LLRF4 board. <http://recycle.lbl.gov/llrf4>
- [7] Tang C, Huang W, Li R, *et al.*, "Tsinghua Thomson scattering X-ray source[J]", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 608(1), pp. S70-S74, 2009.

- [8] Yang J, Du Y C, Yan L X, *et al.* “Laser–RF synchronization based on digital phase detector[J]”. *Nuclear Science and Techniques*, vol. 28(4), p. 57, 2017.