CHARACTERIZATION AND SUPPRESSION OF THE ELECTROMAGNETIC INTERFERENCE INDUCED PHASE SHIFT IN THE JLAB FEL PHOTO – INJECTOR ADVANCED DRIVE LASER SYSTEM*

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Abstract

The drive laser for the photo-cathode gun used in the JLab Free Electron Laser (FEL) facility had been experiencing various phase shifts on the order of tens of degrees (>20° at 1497 MHz or >40ps) when changing the Advanced Drive Laser (ADL) [2][3][4] micro-pulse frequencies. These phase shifts introduced multiple complications when trying to setup the accelerator for operation, ultimately inhibiting the robustness and overall performance of the FEL. Through rigorous phase measurements and systematic characterizations, we determined that the phase shifts could be attributed to electromagnetic interference (EMI) coupling into the ADL phase control loop, and subsequently resolved the issue of phase shift to within tenths of a degree (<0.5° at 1497 MHz or <1ps). The diagnostic method developed and the knowledge gained through the entire process will prove to be invaluable for future designs of similar systems.

INTRODUCTION

From the time of implementation of the JLab FEL Advanced Drive Laser (ADL) and phase control system in early 2009, the accelerator had been experiencing phase shifts/jitter between the electron beam and the injector/linac RF. The timing jitter and drifts were reduced substantially by implementing an analog control loop which provided an additional phase correction signal for very low frequencies into the CLX-1100 controller. However, there was also a phase shift correlated with switching the micro-pulse frequency of the ADL, which was a routine occurrence during FEL tune-up and operations. Although these phase shifts were somewhat quantifiable, they hindered FEL accelerator operations. Preliminary investigations into the stability of the RF reference indicated that the source of the phase shift was introduced somewhere between the reference trigger for the ADL and the FEL injector. Based on this we initiated further investigation and subsequent characterizations of the ADL phase stability.

EXPERIMENTAL DESCRIPTION & PROCEDURE

For this experiment a measurement of DC phase shift as well as low frequency and transient phase shifts was devised. [1] We used an HP 8753C network analyzer to characterize the amount of phase shift in the system. The network analyzer was setup for an S_{21} measurement in a continuous wave (CW) frequency mode at 70 MHz. The S_1 port, i.e. the output, was used to replace the 70 MHz reference signal usually received by the Radio Frequency Control Module (RFCM). The RFCM mixes the 70 MHz signal with a 1427 MHz local oscillator signal, and the resulting 1497 MHz signal is then provided to the FEL ADL clean room via a thermally stabilized cable. In the ADL clean room the 1497 MHz signal is frequency divided by 20, producing a 74.85 MHz signal that is used to both reference and trigger the ADL and its various components. (see Figure 1).

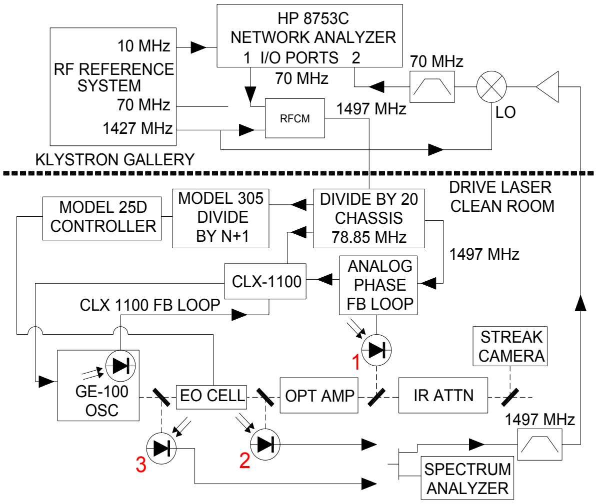

Figure 1. Diagram of the measurement setup.

During the experiment the signals from photodiodes 1 & OSC were sent to the FEL gallery in a similar fashion as the signals from photodiodes 2 & 3 indicated in Figure 1, as well as signals from the divided by 20 chassis and the Conoptics 305 divide by n+1 controller. Photodiode detectors were then used to detect the optical signal produced by the ADL. Two fast photodiodes were in place prior to the experiment (Figure 1, photodiodes 1 & OSC), and another fast photodiode was used to detect and measure the optical beam in other places along the ADL optical beam path (Figure 1, photodiodes 2 & 3). The

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signal from a given photodiode was then sent through a 1497 MHz filter, amplified, and sent back out to the FEL gallery. In the gallery the 1497 MHz signal was mixed with the 1427 MHz signal from the FEL Master Oscillator, producing a 70 MHz signal. This signal was sent through a 70 MHz band-pass filter, and then to the S_2 channel of the network analyzer where a S_{21} measurement was performed to determine the source and magnitude of the phase shifts. Since the 1427 MHz reference was used for both the up and down conversion processes, the measured phase shifts at 70 MHz were the same as the phase shift at 1497 MHz. The sweep time on the network analyzer was set to the minimum 100.5 ms for a 201 point trace, and the system provided a time domain trace of the phase shifts of the selected ADL output. A S_{21} response calibration was then performed which provided an absolute phase accuracy of less than 0.2° pk-pk.

DATA, ANALYSIS & RESULTS

Prior to this experiment beam based measurements clearly indicated a phase shift when switching the micro-pulse frequency of the ADL. Since the only changes that take place when the micro-pulse repetition rate is switched is the frequency and the amount of bias voltage applied to the electro-optical (EO) cell changing the repetition rate of the optical pulse, the EO cell was thought to be the source of the phase shifts. The measurements in Table 1 were taken before the EO cell to see if any noticeable phase shifts of the optical beam occurred. The measurements in Table 2 were taken using the fast photodiode labeled "3" in Figure 1. It should also be noted that unless otherwise stated the feedback loop in Figure 1, labeled as "Analog Feedback Loop," was disconnected from the CLX-1100 for the measurements.

Table 1: Data Taken using Photodiode 3 in Figure 1.

	Phase shift (degrees) when switching frequency			
4.68MHz → 37.4MHz	-150	-140	-110	-100
37.4MHz → 4.68MHz	125	100	100	75
4.68MHz → 18.7MHz	-125	-100	-80	
18.7MHz → 4.68MHz	100	70	50	

Table 2: Data Taken using Photodiode OSC in Figure 1.

	Phase shift (degrees) when switching frequency		
4.68MHz → 37.4MHz	-12	-12	-15
37.4MHz → 4.68MHz	12	12	15
4.68MHz → 18.7MHz	15	15	16
18.7MHz → 4.68MHz	-15	-15	-16

The data recorded indicated a tremendous phase shift occurring before the EO cell, in the optical oscillator portion of the ADL. Operating at 4.68 MHz, although the EO cell had been effectively isolated optically to prevent any optical feedback into the GE-100 oscillator cavity, sidebands were observed at 4.68 MHz intervals on either side of the 74.85 MHz center frequency (74.85 MHz is the operational frequency of the GE-100 optical oscillator and 20th sub harmonic of the FEL). When the EO cell was triggered at other operational frequencies (37.4 MHz, 18.7 MHz, 9.35 MHz, 4.68 MHz, 2.34 MHz, etc.), sidebands were also seen at corresponding intervals from the 74.85 MHz center frequency, despite the EO cell being optically isolated from the GE-100 oscillator.

Based on the observations and data taken, it was deduced that electromagnetic interference (EMI) from the EO cell was coupling into the photodiode detector used in the GE-100 oscillator and affecting the phase of the ADL. The next step was to determine where exactly the EMI was emanating from and how it was coupling into the GE-100 oscillator causing the ADL phase shifts. A loop antenna was made using an SMA connector and piece of insulated wire, and connected to the spectrum analyzer via a high quality shielded RF cable effectively making a RF "sniffer" to pin-point the exact source of the EMI.

After thoroughly probing the EO cell, Conoptics 25D EO cell high voltage driver and Conoptics 305 EO cell controller/trigger, with the RF "sniffer" it was determined that the source of the EMI were the high voltage (HV) cables from the Conoptics 25D to the EO cell.

The manufacturer of the EO cell, Conoptics, was contacted for information on the HV cables used and any advice they could offer on the matter. The manufacturer confirmed our belief that the HV cables were not shielded except for the HV cable connectors, and that other experimenters who had encountered similar problems with EMI had used copper tube for shielding, which is far too rigid and impractical for our application. After some consideration a suitable shielding method was devised. The EO cell HV cables were threaded through stainless steel braided sleeves and the stainless steel sleeves were joined to casing of the high voltage connectors with small diameter stainless steel hose clamps to ensure the shielding had a good contact to ground.

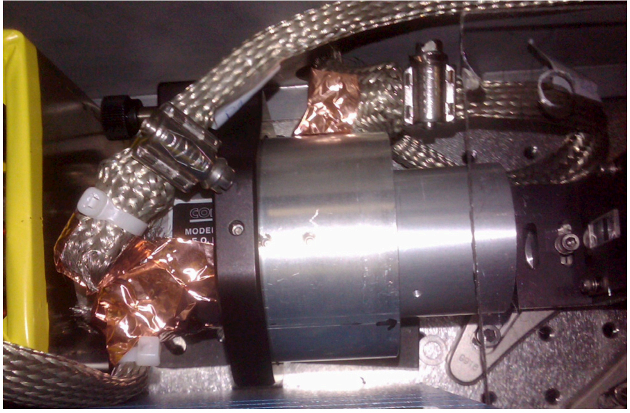

Figure 3. Image of the stainless steel braided sleeves shielding the EO cells HV cables. Copper tape was also used in some places to ensure adequate shielding.

After confirming with the RF "sniffer" that the RF leakage from the shielded HV cables was negligible, measurements were taken again with the network analyzer in the FEL gallery using the photodiode in the GE-100 oscillator cavity. (Photodiode OSC in Figure 1) The phase shift measurements taken using the EO cell HV cables shielded with the stainless steel braid are given in Table 3.

Table 3. The resolution of the network analyzer was calibrated for an accuracy of 0.1º but the signal noise of ~0.2º was observed and could not be eliminated for these measurements.

Phase shift (degrees) when switching frequency				
4.68MHz → 37.4MHz	0.6	0.5	0.4	0.6
37.4MHz → 4.68MHz	-0.5	-0.6	-0.5	-0.4

The measurements taken using the network analyzer in the FEL gallery and the photodiode in the GE-100 oscillator cavity indicated that the phase shifts had been adequately suppressed for FEL operations after taking into account ~0.2º signal noise observed on the network analyzer. The results seen using the network analyzer and photodiode in the oscillator cavity ("OSC" in Figure 1) were later verified using a Streak Camera to monitor the optical beam after the EO cell and IR Attenuator ("IR Attn" in Figure 1). The Streak Camera used had a resolution of 0.7 pS (corresponding to ~ ≤ 0.5º at 1497 MHz) and no phase shift of the ADL optical beam was observed when taking measurements using the Streak Camera. The Streak Camera had been used in previous measurements and confirmed the same amount of phase shift as was measured with the network analyzer. A final check for ADL phase shifts was done using photodiode 1 (Figure 1), the fast photodiode used by the Analog Feedback Loop to control the slower drifts of the ADL. When the phase measurements were taken using photodiode 1 a phase shift was once again observed despite the shielding on the EO cell HV cables.

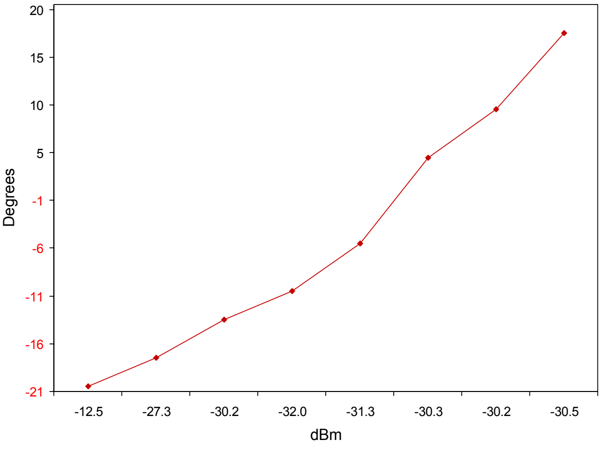

Figure 4: Phase shift as a function of RF power at 1497 MHz for an optical detector used in this system.

Concerned that there was an amplitude correlation to the phase shift measured by one of the photo diodes we performed a separate experiment where a polarizing crystal and half-wave plate were used to attenuate the signal that was subsequently sent to a photo diode. Using the same techniques described above, we measured the phase shift as a function of the amplitude of the 1497 MHz component of the diode signal. The results of this experiment are shown in Figure 4. Because of this effect photodiodes 2 and 3 (Figure 1) could not be used during operation because the mirrors used to send beam to either of these photodiodes blocks the optical transport. Thus, it was decided to split the signal coming from photodiode "OSC" (Figure 1) using an RF splitter with a DC to 4.2 GHz bandwidth.

One of the signals was then sent to the CLX-1100 as before for the manufactures control loop, and the second signal was sent through a 1497 MHz filter, amplified, and used for the analog feedback loop shown in figure 1. Photodiodes 2 and 3 (Figure 1) were then used one at a time with the network analyzer in the FEL gallery to monitor any phase shift. Similar results to those given in Table 3 were recorded with both photodiodes, and then successfully verified with a Streak Camera.

CONCLUSIONS

After considerable efforts, the source of the phase shifts observed in the FEL electron beam when changing the ADL micro-pulse frequency were discovered, quantified, and suppressed to what has proven to be acceptable levels, within 0.5º phase at 1497 MHz. A novel approach to measure phase shift developed and used to accurately measure the very low frequency phase shifts associated with the system. The initial electron beam based results seen when brining the FEL back online indicated the phase stability of the machine (and ADL) had greatly improved, and phase shifts due to changing the were recorded with both photodiodes, and then successfully verified with a Streak Camera.

A great deal of valuable knowledge was gained during the course of this experiment, which should prove to be invaluable when updating the ADL or designing the next generation drive laser and synchronization systems for future light sources.

REFERENCES

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