SLAC-PUB-9468
August 2002

Phase Noise Characterization of the Main Drive Line at SLAC

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August 8, 2002

Prepared in partial fulfillment of the requirements of the Department of Energy's Energy Research Undergraduate Laboratory Fellowship under the direction of Ron Akre in the Klystron department of the technical division at the Stanford Linear Accelerator Center.

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Work supported by the Department of Energy contract DE-AC03-76SF00515.

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Abstract

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The phase noise of the Main Drive Line (MDL) at the Stanford Linear Accelerator Center is extremely important to the operation of the linac since the MDL provides the radio frequency (RF) drive and phase reference for the entire accelerator system. In order to ensure that the Linac Coherent Light Source (LCLS) can be run using current MDL components, the phase noise of the MDL had to be ascertained. This was determined using an ultra-stable reference oscillator phase-locked to the MDL. Using this device, the phase noise was determined to be far greater than LCLS requires. This suggests that an improved Master Oscillator needs to be obtained in order to be able to run LCLS on the SLAC linac.

Introduction

The Stanford Linear Accelerator Center (SLAC) maintains the largest linear accelerator (linac) in the world, with a length of approximately 3 *km* (Neal, 1968). Forty years after it first became operational, SLAC is still one of the world's leading research institutions (McDunn, 2002). The SLAC linac is powered by 240 klystrons, devices that are used to amplify radio frequency (RF) electromagnetic radiation by velocity modulation of a high-power electron beam. The linac is divided into 31 sectors, each with its own subbooster klystron that provides RF for several high-power accelerator klystrons (Schwarz, 1985).

The Main Drive Line (MDL) of the linac provides the RF for all of the accelerator components. The MDL, which runs the entire 3 *km* length of the accelerator, supplies RF at a frequency of 476 *MHz* to the klystrons and timing apparatus in each of the 31 sectors of the accelerator. At the beginning of each sector, the RF provided by the MDL is multiplied by six to achieve the proper S-band frequency of 2856 *MHz*. This frequency is then delivered to the Phase Reference Line (PRL) and to the subbooster klystron. The PRL provides the phase reference for the entire 100 *m* length of each sector. The subbooster klystron provides the RF drive for each of the eight accelerator klystrons in the sector. These klystrons provide the RF for the electron beam of the linac (Jobe, 1989). Since the MDL provides the RF drive and phase reference for the entire accelerator system, the RF phase stability of all accelerator components is dependent on it. Therefore, the amount of phase noise present on the MDL is of paramount importance to the functionality of the accelerator itself.

The phase noise of the MDL is especially crucial when considering the Linac Coherent Light Source (LCLS). LCLS is a SLAC project designed to create extremely bright 1.5 *Å* x-rays using a dense 15 *GeV* electron beam. In order to run LCLS, the electron bunches have to have nominal peak currents of 3.5 *kA* and lengths of 70 *fs*. These restrictions require the RF system on the current linac to perform at an unprecedented level (Akre, 2000). Recent calculations suggest that in order to run LCLS on the SLAC linac, the timing jitter[1] of the MDL must be better than 50 *fs* (or 0.05° RMS at 2856 *MHz*) in order to measure the required beam phase to 70 *fs* (Emma, 2002). Therefore, calculations of the phase noise inherent to the MDL are required to determine if the current MDL system is adequate to run LCLS.

The Master Oscillator provides the original frequency source driving the MDL in Sector 0. This signal is passed through the Master Amplifier and then on to the MDL. Both Sector 0 and Sector 30 have a monitor port that relays information about the MDL for testing. All of these components have phase noise associated with them. Taking phase noise measurements of any instrument will give the phase noise of that specific instrument as well as the phase noise of every instrument before it in the line. Therefore, the MDL monitor in Sector 0 contains the phase noise of both itself and the Master Oscillator.

This project entailed using an ultra-stable reference oscillator phase-locked to the MDL in order to determine the phase noise present on the MDL. The operational bandwidth of the phase noise measurement system was determined in order to ensure that the frequency data used in analysis was accurate. RMS phase variations over different

[1] In the time domain, timing jitter is the proper term to use. In the frequency domain, phase noise is proper. Therefore, the Fourier transform of the timing jitter can be expressed as phase noise. The phase noise associated with an instrument is often measured by its timing jitter in *fs*.

bandwidths were calculated from phase noise plots. The phase noise was measured at different locations on the MDL to determine if each of the instruments used met LCLS requirements. Since these measurements were done during accelerator downtime, possible phase noise contributions from high power modulators and klystrons were not present in the data. Further, since the interferometer is gated off when the beam is operational, it will not contribute noise to the beam from an LCLS standpoint. Therefore, when taking noise measurements, the interferometer was turned off so that it did not introduce any noise into the data.

All data collected from the MDL were analyzed using the programming software Matlab. A Blackman window was used to ensure the endpoints of the data interval were equal. This eliminates the effects of a finite time fast Fourier transform. The Blackman window function was chosen because it seemed to provide the best signal-to-noise ratio in a test program when compared to the other options. The data collected from the MDL were transformed from the time domain into the frequency domain using the fast Fourier transform algorithm. The total phase noise of the system, measured in *dBc*, was determined by calculating the integral of the transformed data over the interval on which the data was collected. This phase noise was converted into a timing jitter measured in *fs* and compared to the LCLS specification of 50 *fs*.

Materials and Methods

In order to determine the phase noise inherent to the MDL, a proper phase noise measurement device needed to be constructed. A common method for determining the phase noise present in a system is to use a phase-locked loop (PLL). In a PLL, the output of the device under test (DUT) is mixed with that of an oscillator phase-locked to the

DUT. The mixer outputs the difference between the two signals, which is interpreted as the phase noise of the system. A schematic of the phase noise measurement system used in this experiment is shown in Figure 1. The data collected by the phase noise measurement system was input into a computer through a scope card. The information obtained by the scope card was then analyzed by a computer program to determine the total phase noise.

Prior to collecting data from the MDL, the specific bits per radian conversion for the phase noise measurement system was determined to be $1.33\times10^{5}\ bit/rad$ when the device was collecting data whose power was 0.5 *mW*. This conversion was inserted into the computer program that analyzed the data collected by the scope card. Since this conversion was determined for incoming data at 0.5 *mW*, all data collected from the MDL had to be at this power as well. Therefore, a variable attenuator was connected to the input of the phase noise measurement device that allowed adjustments to be made to the incoming signal's power at each point on the MDL.

In order to determine the operational bandwidth of the phase noise measurement system, a frequency generator was used to test the output of the device under various frequencies. At lower frequencies, the peak of the device became dampened. Therefore, the device was determined to be unfit to record data at frequencies below 5 *Hz*. However, to ensure that the data collected was reliable, the lower limit was set to 10 Hz. The power ratios of the peaks obtained at different frequencies are shown in Table 1 along with the associated uncertainty.

The phase noise measurement system was then used to determine the short-term phase noise present at several different locations on the MDL. In Sector 0, phase noise measurements were taken at both the outputs of the Master Oscillator and the MDL monitor. In Sector 30, the phase noise was determined at only the output of the MDL monitor. Phase noise measurements were also taken when the phase noise measurement system was disconnected to all outside sources. This provided a background noise measurement that could be subtracted out of the data received from the MDL. An example of the plots of the raw data, the windowed data, the Fourier transformed data, and the integrated data are shown in Figure 2. The examples come from the MDL monitor in Sector 0.

The PEP-II phase shifter that is usually present in Sector 0 was also tested. However, since it was removed from Sector 0 in order to aid in the creation of a new phase shifter, its phase noise was determined in a laboratory using a Master Oscillator similar to the one present on the MDL. Therefore, to accurately determine the phase noise inherent to the PEP-II phase shifter, the phase noise of the oscillator used in the laboratory also needed to be determined.

To increase the confidence in the data, five phase noise measurements were taken at each location on the MDL and in the laboratory. All of the data collected from the MDL were entered into a computer program to determine the overall phase noise of the system at each point. The overall timing jitter was plotted to show the relation between the jitter at different locations on the MDL and in the laboratory. From these plots and from the data gathered from the program, the total timing jitter could be compared to the requirements set by LCLS.

Results

The timing jitter inherent to all measurements on the MDL was found to be in the range of 250-450 *fs*, anywhere from five to nine times the acceptable value required by LCLS. This was the timing jitter associated with all frequencies from the start frequency to 20 *kHz*. However, since the bandwidth of the measurement device did not allow direct noise measurements at frequencies below 10 *Hz*, the total timing jitter between 10 *Hz* and 20 *kHz* was used. In this case, the total timing jitter was in the range of 225-325 *fs*. Table 2 shows the exact timing jitter from the start frequency to 20 *kHz* and from 10 *Hz* to 20 *kHz*, measured in *fs*, recorded at each point on the accelerator or in the laboratory along with the associated uncertainty. The values for the timing jitter between the start frequency and 20 *kHz* and between 10 *Hz* and 20 *kHz* are shown pictorially in Figure 3 with respect to the accepted phase noise level required for the operation of LCLS.

In order to better display the spectral content, a backwards integration[2] of the transformed data collected at each point was calculated and plotted. The plot shows the frequencies that contributed the most to the phase noise of the system. These frequencies are represented by sharp jumps in the timing jitter on the plot. The plots of the backwards integrals of the data collected from the MDL monitor and the Master Oscillator in Sector 0, from the MDL monitor in sector 30, and from the phase noise measurement system by itself are shown in Figure 4. Further, the plots of the backwards integrals of the data collected from the PEP-II phase shifter, from the Master Oscillator in

[2] Each point on the plot of a backwards integral is the total integral from the point's x-coordinate to the endpoint of the x-interval. For instance, in Figure 4, the point on the plot corresponding to the MDL monitor in Sector 0 at 10 *Hz* is 296.71 *fs*. This means that the total timing jitter associated with the MDL monitor in Sector 0 over the interval from 10 *Hz* to 20 *kHz* is 296.71 *fs*.

the laboratory, and from the phase noise measurement system by itself are shown in Figure 5.

Figure 4 shows that the key contribution to the phase noise at each point on the MDL comes at the frequency of around 680 *Hz*. At present, it is not known what this contribution is caused by, however it is believed that it is associated with the Master Oscillator. Also in Figure 4, another slight jump is located at a frequency of around 60 *Hz*. This jump is associated with the frequency provided by common power outlets and can be minimized with proper power cord usage. Figure 5 shows that the key contribution to the phase noise in the laboratory comes at a frequency of around 60 *Hz*. Once again, this is introduced by the power cords near the system. However, in both cases, eliminating these peak frequencies will still not bring the phase noise of the system within LCLS requirements.

The data represented in Figure 4 suggests several strange things about the data collected from the MDL. First of all, the MDL monitor in Sector 30 seems to have a lower average phase noise than that in Sector 0. This could be due to the 680 *Hz* noise component changing with time between measurements. Outside of the 680 *Hz* noise component, the Master Amplifier and MDL do not contribute a measurable amount of noise and therefore measurements from the MDL monitors cannot be accurately compared. Another problem is that the phase noise measured at the MDL monitors in Sector 0 and Sector 30 should contain the phase noise present in the Master Oscillator in Sector 0. At frequencies above 60 *Hz*, this is entirely possible. However, below 60 *Hz*, the timing jitter of the Master Oscillator far exceeds either MDL monitor. This, along with a much higher standard error of the Master Oscillator data sets, suggests that the

Master Oscillator data below 60 *Hz* is not entirely reliable. This is a higher frequency than that determined as the lower limit of the phase noise measurement system's operational bandwidth. Better measurements should help to correct this error.

Using the data from Figure 4 at frequencies above 60 *Hz*, however, suggests several interesting and encouraging things. Since the MDL monitors contain the phase noise present in the Master Oscillator, the phase noise introduced by all other MDL components seems to be fairly low. This suggests that with a better Master Oscillator, far better phase noises can be achieved. The same can be seen in Figure 5. The phase noise introduced by the PEP-II phase shifter by itself is small and not measurable with the existing Master Oscillator.

Discussion and Conclusions

The phase noise present on the MDL was found to be far above the acceptable value specified for the functionality of LCLS. Therefore, before LCLS can be run at SLAC, the RF source for the MDL will have to be modified or replaced. It is believed that the primary cause for such high phase noises on the MDL and in the laboratory was the Master Oscillator used. While it appeared that the Master Oscillator in the laboratory had a lower phase noise than the one on the MDL, both oscillators had phase noises far above LCLS specifications.

In order to bring these phase noises below LCLS specifications, two things must be accomplished. First of all, the Master Oscillator on the MDL must have a phase noise far lower than that currently measured. Therefore, this oscillator must be replaced with a much quieter model. Second, the cause of the phase noise shift corresponding to the frequency of 680 *Hz* must be determined, and its contribution to the total phase noise of the system must be decreased. Since it is believed that the 680 Hz noise component is caused by the Master Oscillator, replacing the oscillator may solve both problems. Fortunately, the peak corresponding to 60 *Hz* on the MDL does not seem to introduce enough phase noise into the system to be a problem. Therefore, it seems that with a better Master Oscillator, the phase noise inherent to the MDL could become low enough to meet LCLS specifications.

Acknowledgements

I would like to thank the United States Department of Energy for sponsoring my research this summer and the Stanford Linear Accelerator Center for providing me with the facilities to conduct this research.

I would also like to thank my mentor Ron Akre of the Klystron department and all others involved with my summer research experience, especially David Steele and Josh Gold for helping me collect data from the linac. Further, I would like to thank Dr. Helen Quinn and Dr. Sekazi Mtingwa for organizing this program and helping to make this experience the best it could possibly be.

This work was performed at the Stanford Linear Accelerator Center, a national scientific user facility sponsored by the United States Department of Energy, in fulfillment of the Energy Research Undergraduate Laboratory Fellowship program.

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Figures

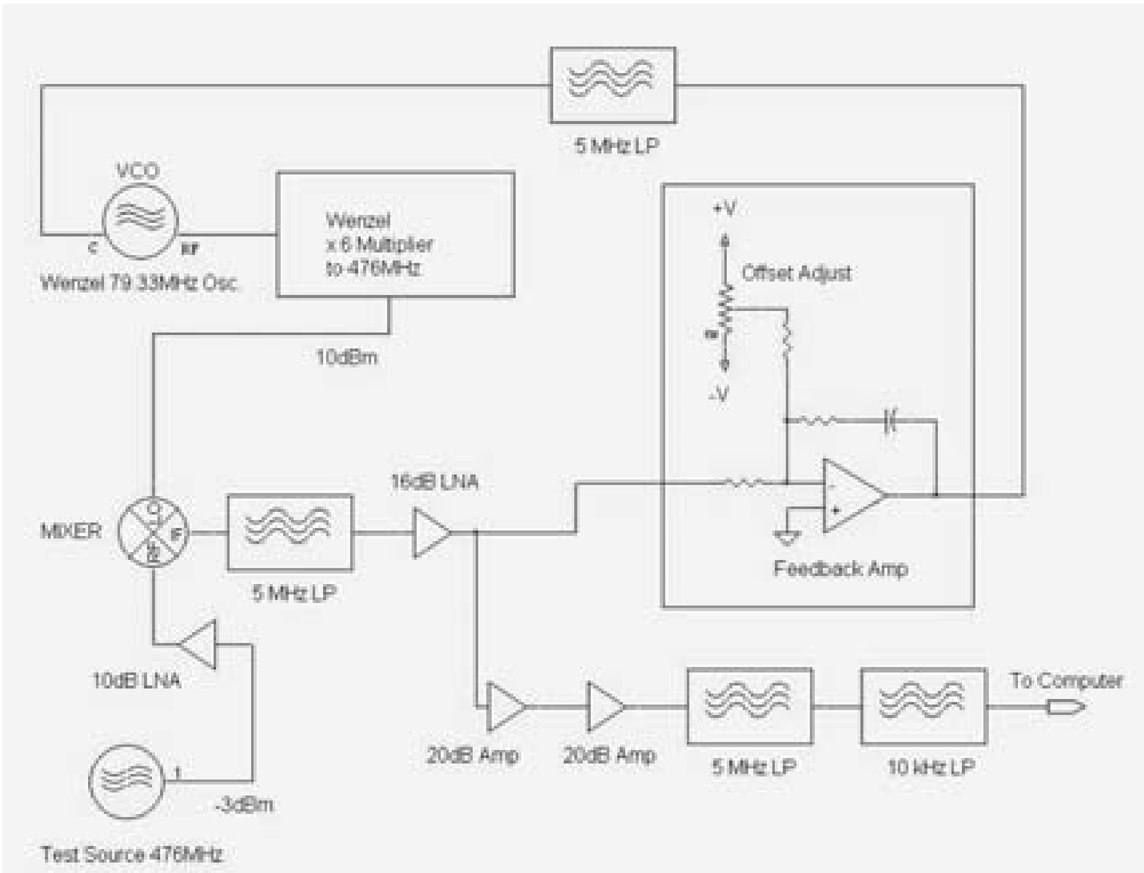

Figure 1: Phase Noise Measurement System

The voltage controlled oscillator (VCO) is phase-locked to the test source and these two signals are mixed together. The output of the mixer is determined to be the phase noise of the system. The system runs at 0.5 mW and has a bits per radian conversion of $1.33\times10^{5}\ bit/rad$.

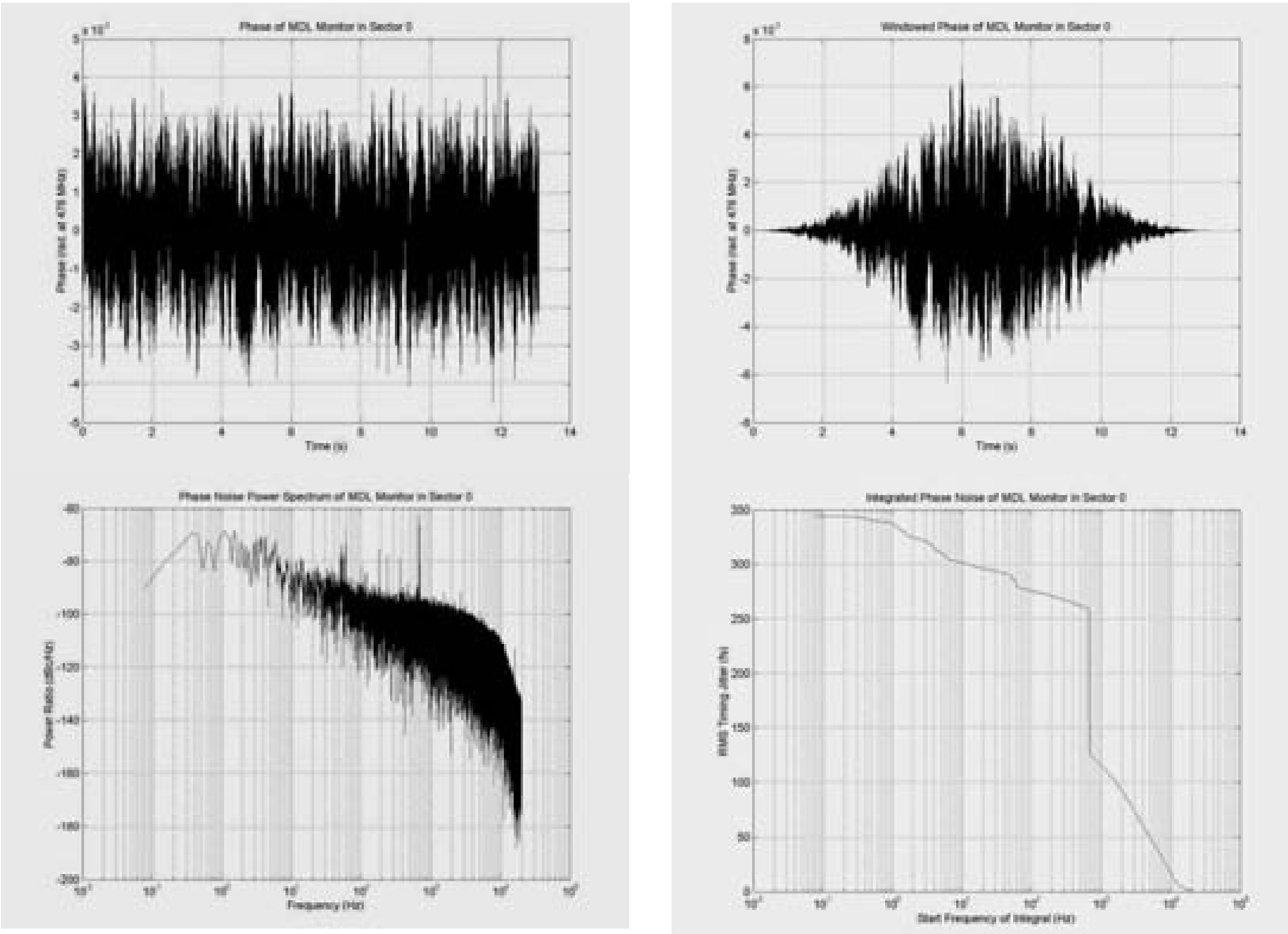

Figure 2: Examples of MDL Data

The figure on the top left is the raw data collected by the scope card from the phase noise measurement system. The figure on the top right shows the data after it has been multiplied by the Blackman window function. The figure on the bottom left shows the Fourier transform of the data on a log plot. The figure on the bottom right shows the backwards integral of the data. Notice that the jump on the plot of the integrated data corresponds to the sharp peak at 680 *Hz* on the plot of the transformed data. All data was collected from the MDL monitor in Sector 0.

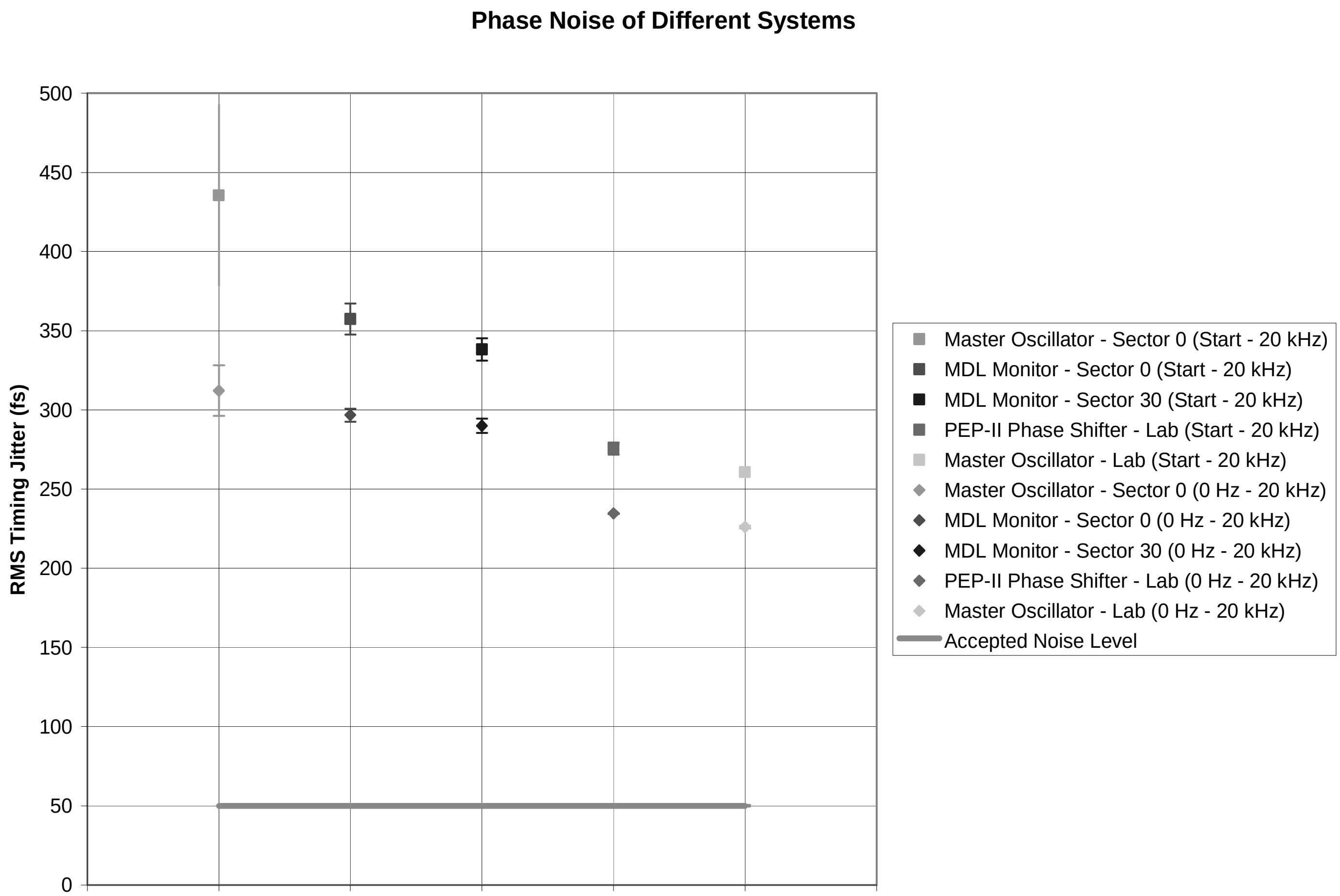

Figure 3: Phase Noise of Different Systems

This shows the total phase noise measured from the different components on the MDL. The total phase noises from the start frequency to 20 *kHz* are shown as the square data points. The total phase noises from 0 *Hz* to 20 *kHz* are shown as the diamond data points (all of which are below the square data points). The accepted noise level required by LCLS is shown as the orange line.

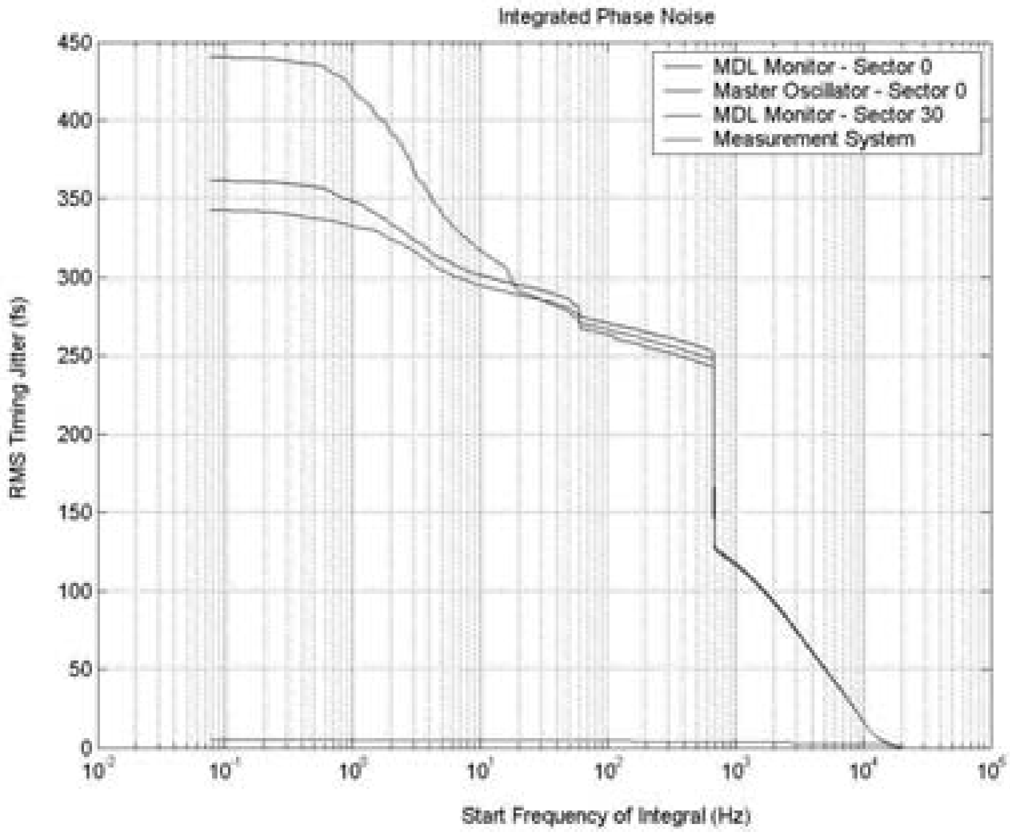

Figure 4: Integrated Phase Noise on MDL

This is the plot of the backwards integral showing the instrumentation tested on the MDL. The x-axis is the start frequency of the integral, which integrates up to 20 *kHz*.

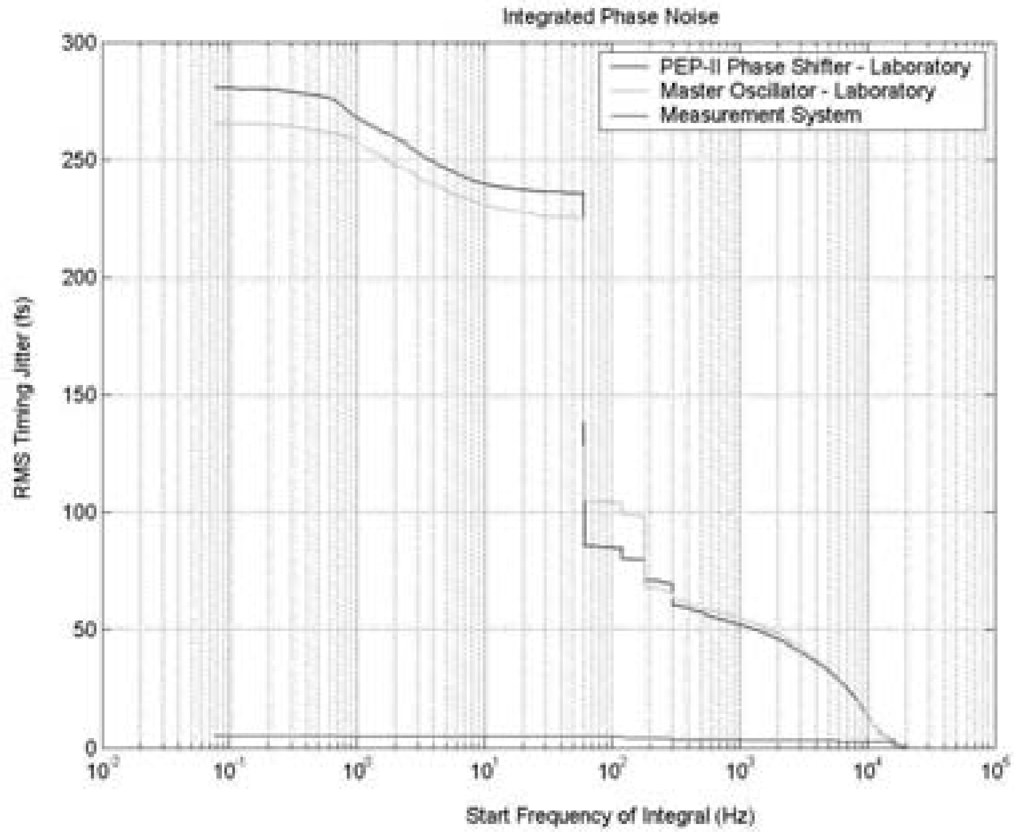

Figure 5: Integrated Phase Noise in Laboratory

This is the plot of the backwards integral showing the instrumentation tested in the laboratory.

Tables

Frequency (Hz)	Power Ratio (dBc)	Avg. Power Ratio (dBc)	Frequency (Hz)	Power Ratio (dBc)	Avg. Power Ratio (dBc)
1000	-67.366 -67.498 -67.375 -67.455 -67.455	-67.430±0.025	10	-71.461 -70.861 -71.031 -70.909 -70.897	-71.032±0.111
500	-69.719 -69.586 -69.686 -69.548 -69.538	-69.615±0.037	7	-69.362 -69.396 -69.374 -69.285 -69.296	-69.343±0.022
100	-68.904 -68.834 -68.878 -68.999 -68.956	-68.914±0.029	5	-79.325 -78.642 -77.908 -77.923 -76.877	-78.135±0.409
50	-69.972 -69.877 -69.900 -69.916 -69.862	-69.906±0.019	2	-78.311 -78.370 -78.321 -78.514 -78.000	-78.303±0.084
20	-69.227 -69.102 -69.070 -69.000 -69.088	-69.097±0.037	1	-84.797 -86.705 -84.948 -90.303 -87.264	-86.803±0.998

Table 1: Power Ratios of Measurement System

The power ratios at each frequency were determined by measuring the specific frequency's peak. Below 5 *Hz*, the power ratio drops off below acceptable levels. However, to ensure that all data collected is reliable, any frequencies below 10 *Hz* were also considered unfit.

Source	Timing Jitter Start - 20 kHz (fs)	Avg. Timing Jitter Start - 20 kHz (fs)	Timing Jitter 10 Hz - 20 kHz (fs)	Avg. Timing Jitter 10 Hz - 20 kHz (fs)
Master Oscillator Sector 0	596.54	435.46±57.177	370.91	312.05±15.978
	562.86		335.33	
	339.94		290.99	
	350.20		287.48	
	353.08		299.88	
MDL Monitor Sector 0	344.30	357.37±9.8138	301.78	296.71±4.0855
	374.06		304.55	
	343.59		286.12	
	355.65		306.15	
	394.59		309.28	
MDL Monitor Sector 30	352.99	338.18±7.0716	307.81	289.86±4.4943
	365.70		296.68	
	336.36		298.16	
	333.11		289.99	
	328.04		281.00	
PEP-II Phase Shifter Test Lab (Usually in Sector 0)	288.33	275.51±3.8312	239.54	234.94±0.24618
	281.15		240.46	
	267.84		240.16	
	287.81		239.36	
	277.74		239.54	
Master Oscillator Test Lab	271.93	260.58±2.9015	232.50	226.01±0.82027
	262.60		230.08	
	270.51		229.24	
	266.82		229.56	
	256.34		233.03	
Measurement Device	5.0109	5.0636±0.069594	4.9825	4.4685±0.034775
	5.0748		4.8367	
	5.0157		4.8908	
	5.3177		4.7703	
	4.8990		4.8621	

Table 2: MDL Instrumentation Phase Noise

The first data column shows the total timing jitter recorded at each location from the start frequency to 20 *kHz*. The second column is simply the average of the five data sets at each location with an uncertainty equal to their standard error. The third column is the timing jitter between 10 *Hz* and 20 *kHz*. The fourth column contains the averages. Both columns of averages have the background timing jitter introduced by the measurement device subtracted out.