SLAC–PUB–8458
June 2000

Performance of the Prototype NLC RF Phase and Timing Distribution System[*]

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Contributed to the 9th Beam Instrumentation Workshop (BIW 2000),
Cambridge, MA., May 8 – 11, 2000

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[*] Work supported by Department of Energy contract DE–AC03–76SF00515.

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Abstract. The proposed 1TeV cm. Next Linear Collider accelerator will require phase synchronization throughout its 30 kilometer length. Phase stability of ~20 degree X-band (11.424 GHz) long term, and ~0.3 degrees X-band short term are required. A prototype fiber optic distribution system has been constructed to demonstrate this level of performance. This system operates by measuring the optical round trip time in the fiber, and then controlling the fiber phase length to stabilize this measurement. We describe the design of this system, and show recent results on stability and phase noise.

TIMING AND RF DISTRIBUTION SYSTEM REQUIREMENTS

The NLC requires trigger synchronization relative to the beam at the 100 picosecond level, and RF phase stability at the 1 degree X-band (0.2 picosecond) level over the ~30 kilometer length of the machine. Since the second requirement is the more stringent, we have designed the timing distribution system to use the same hardware as the RF distribution system. The RF timing requirement corresponds to a $\Delta L/L$ stability of $<2.5\times10^{-9}$, which would be impractical without feedback.

It is assumed that RF phase measurements relative to the electron beam will be used to obtain long term stability. The RF distribution system needs to maintain the RF phase to within 20 degrees X-band ($<5\times10^{-8}$) for long periods of time when the beam is not running.

In the proposed system, and in the prototype system, the RF phase transmission frequency is 357MHz (1/32 of the main X-band). Triggers throughout the machine operate by counting cycles of 357 MHz starting from a fiducial pulse superimposed on the RF.. The countdown timing system is similar to the PDU (programmable delay units) already in use on the SLAC main LINAC. The R+D to date has concentrated on the RF system stabilization

The phase and timing distribution system must have high reliability. We plan to achieve this with a single point failure resistant redundant system.

TABLE 1. RF Distribution System Performance Requirements.

Parameter	Requirement
System Length	30 Km
RF Phase Stability (short term <1 minute)	1 degree X-band
RF Phase Stability (long term)	20 degrees X-band
RF Phase Noise	1 degree X-band in 100Hz Bandwidth
Reliability	>1000 Hour MTBF system wide

SYSTEM DESIGN

The Phase distribution system consists of the following components. A master oscillator located at the center of the machine. Long links to each of the 44 machine sectors. A sector phase reference to distribute RF through the approximately 600 meters of tunnel. And a phase comparison system which is used to compare the distribution RF phase with the beam phase.

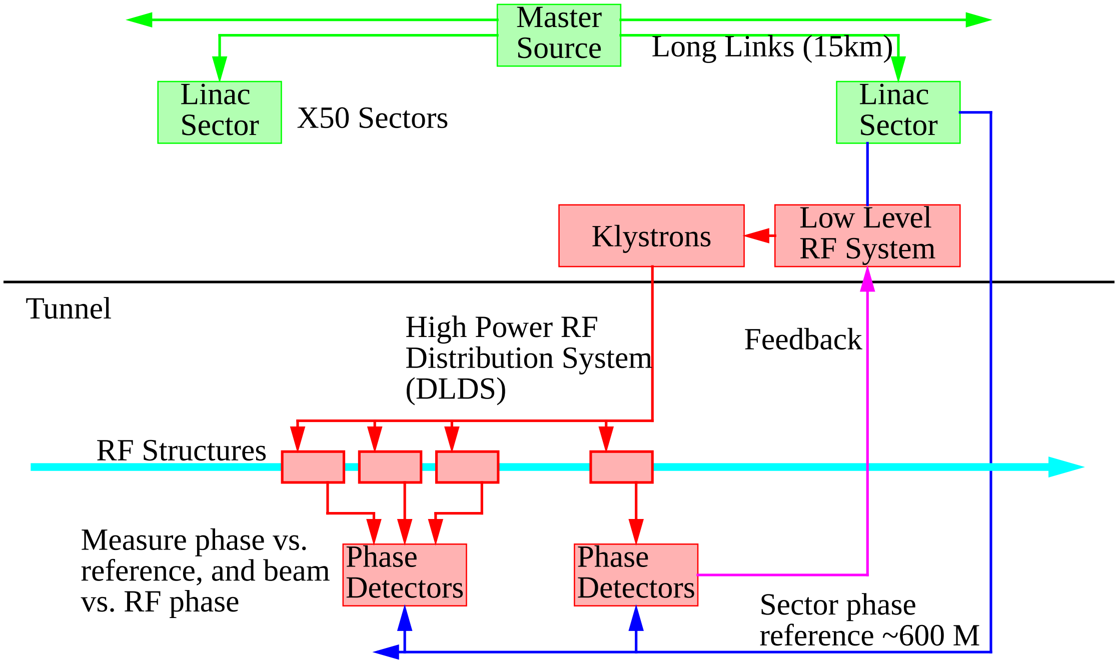

FIGURE 1. Overall layout of RF phase distribution system

Master Source

The requirements on the master source for phase noise and frequency stability are determined by the time delay of the distribution system and the phase noise and stability requirements. Both are easily met with conventional systems. We plan on using a commercial GPS disciplined Rubidium source which exceeds the requirements.

Long Link System

Fiber optics and coax distribution were both considered for this system. They have similar phase length vs. temperature coefficients of ~10^{-5}/°C. Note that the primary contribution to temperature coefficient in fiber is the change in refractive index, not the change in length. Fiber was used due to its lower cost and higher bandwidth. Without the use of feedback, the long term phase stability requirement of 20 degrees X-band would require an impractical fiber temperature stability of .005 °C.

Fibers are run point to point from the central master source to each of the 44 sectors. An adjustable phase length fiber is connected in series with the main fiber. The far end of the main fiber is terminated with a fiber mirror. The transmitter measures the phase of the light reflected from the far end of the fiber and adjusts the phase length to hold the reflected phase stable. Assuming that the forward and backward traveling optical signals propagate at the same speed (or more precisely that the temperature coefficients of velocity are the same) the phase of the outgoing signal is stabilized.

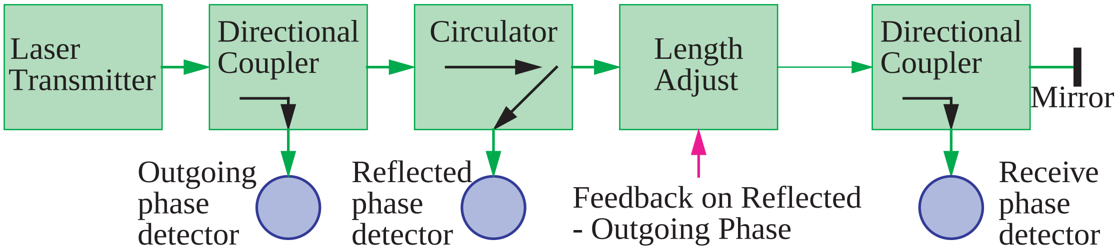

FIGURE 2. Long Link Schematic. Length adjust can be a length of fiber in a temperature control oven

Several phase length adjust systems have been considered. If the fiber is to operate in a standard trench without temperature control, 10°C temperature variations are expected, corresponding to length changes on the order of a meter. A spool of fiber whose phase length is adjusted by the temperature of an oven has been found to work well.

R+D is also proceeding on a wavelength tunable laser system. The change in phase length in the main fiber due to dispersion and the change in laser wavelength would provide the feedback mechanism. A tuning range of approximately 40 nanometers with <0.5 picometer step size is required. This is currently beyond the state of the art for compact commercial tunable lasers, however developments in DWDM (dense wavelength division multiplexing) communications systems may provide the required tunable laser technology.

High reliability is obtained through redundancy. The system is fully redundant to the control crate where the final phase signal is received. In that crate a module (Phase Control Unit) will automatically switch over to the second line if the first fails or has excessive phase noise.

The electron beam in the NLC has sufficient density to damage the accelerator if the accelerating structures are mis-phased. In order to prevent this, the phase control unit contains a high stability local oscillator which is able to maintain its phase between machine pulses (8 milliseconds). If the master source, or part of the transmission system were to suddenly shift phase, the phase control unit will still broadcast the correct phase to its local crate, and then signal the machine protection system to abort the next pulse. Failures of the phase control unit will only affect the local crate and cannot damage the machine through incorrect phasing.

Sector Phase Reference

The sector phase reference must meet specifications similar to those for the long fiber links. Phase information must be provided to typically 50 devices in the tunnel in each sector. The radiation in the tunnel (estimated at ~1 R/Hour) prohibits the use of fiber optics for distribution. The large device multiplicity makes a point to point system similar to the long fiber links impractical.

We plan on a scheme where RF reference signal is phase locked to the master source (through the long fiber links) at the far end of the cable from the transmitter. At each device the forward and backward going phases are compared. The average of the forward and backward phase should not depend on changes in the phase length of the cable. This system needs to provide a factor of 10 improvement over a standard coax cable in the tunnel in order to meet the phase stability requirements. The extent to which reflections from the couplers will degrade the accuracy of the system has not yet been calculated.

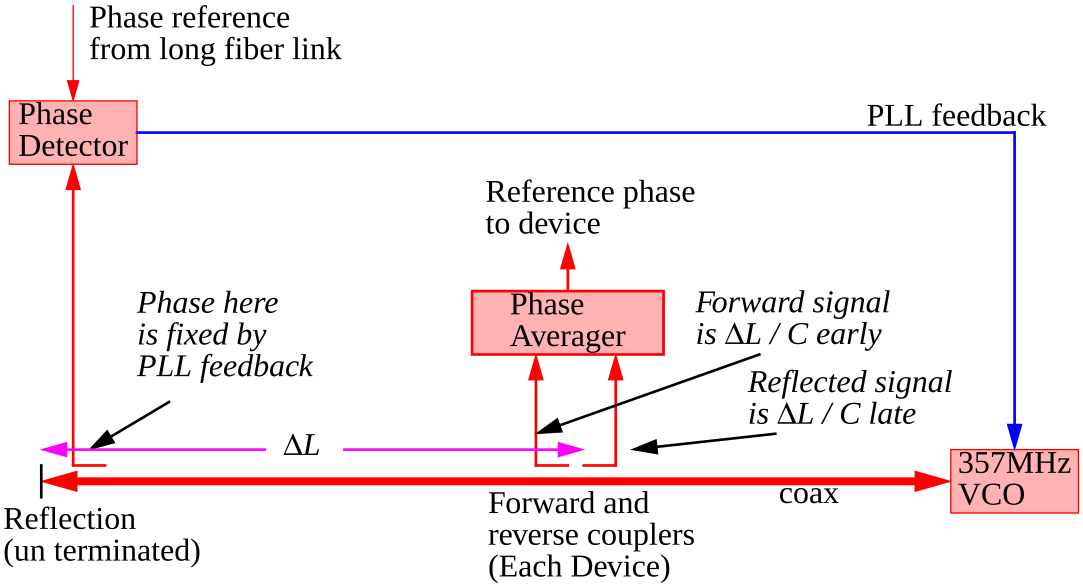

FIGURE 3. Sector Phase Reference Line

Beam Phase Reference

The phase reference system is adjusted on long time scales to match the electron beam phase. The electron beam phase is measured by comparing the fields induced in the accelerating structures with the main RF power in the RF structures. The beam induced fields are typically ~20dB below the RF fields for full power operation and ~70dB down for operation with a single low current bunch. There are two schemes under consideration for the measurement.

The RF can be disabled on a group of structures for a single pulse, and the beam induced fields measured. If an additional group of structures which had been inactive is activated during that pulse, the effect on the beam should be small. The alternative method is to measure the RF phase from the structure before, during, and after the beam pulse. Due to the small beam power relative to the main RF power, this measurement will require a large number of averages (~1000 for low current single bunch operation).

LONG FIBER LINKS – EXPERIMENTS

A phase transmission test system has been constructed to demonstrate the basic technology. With a few minor upgrades this system is expected to meet the requirements of the NLC long fiber link system.

TABLE 1. Test System Status

Parameter	NLC Requirements	Test System Performance
Transmission distance	1 – 15 Kilometers	15 Kilometers
Fiber temperature range	+/- 5°C	+/- 5°C (+/-10°C expected)
Long term phase stability	+/- 20° X-band	+/- 2°X-band over 3 day run
Phase temperature coefficient	<4° X-band / °C	<0.4°X-band / °C
Phase noise	<0.3° X-band in 10 Hz BW	0.2° X-band in 10 Hz BW (short term), 1° long term

Test System Design

The system uses a 15 kilometer spool of single mode fiber (SMF-28) in a temperature controlled oven to simulate the long fibers in the trenches. The RF phase is transmitted at 357 MHz (1/32 of the main X-band frequency) by directly modulating the current of a 1550 nanometer, 1 milliwatt laser.

Fiber phase length control is performed with a 6 kilometer spool in a temperature controlled box. The box is cooled by a thermoelectric cooler to a minimum temperature of 0°C. A fan in the box blows air over a wire grid heater and directly onto the fiber spool to provide a maximum temperature of 50°C. The fan and wire grid provide fast response times of a few tens of seconds.

Phase is measured by down mixing with a 357.025 MHz LO signal. The resulting 25KHz IF signal is digitized at 200 KHz and digitally phase detected. The diode laser is pulsed (100µs) to allow the same electronics to receive all three signals. In the real system, the fiber end signal is received by separate electronics located at each sector.

The phase difference between the forward going signal and the reflected signal are use to feed back with a standard PID loop on the temperature of the box with the 6 kilometer fiber. Phase detection and feedback are performed with a Windows NT PC.

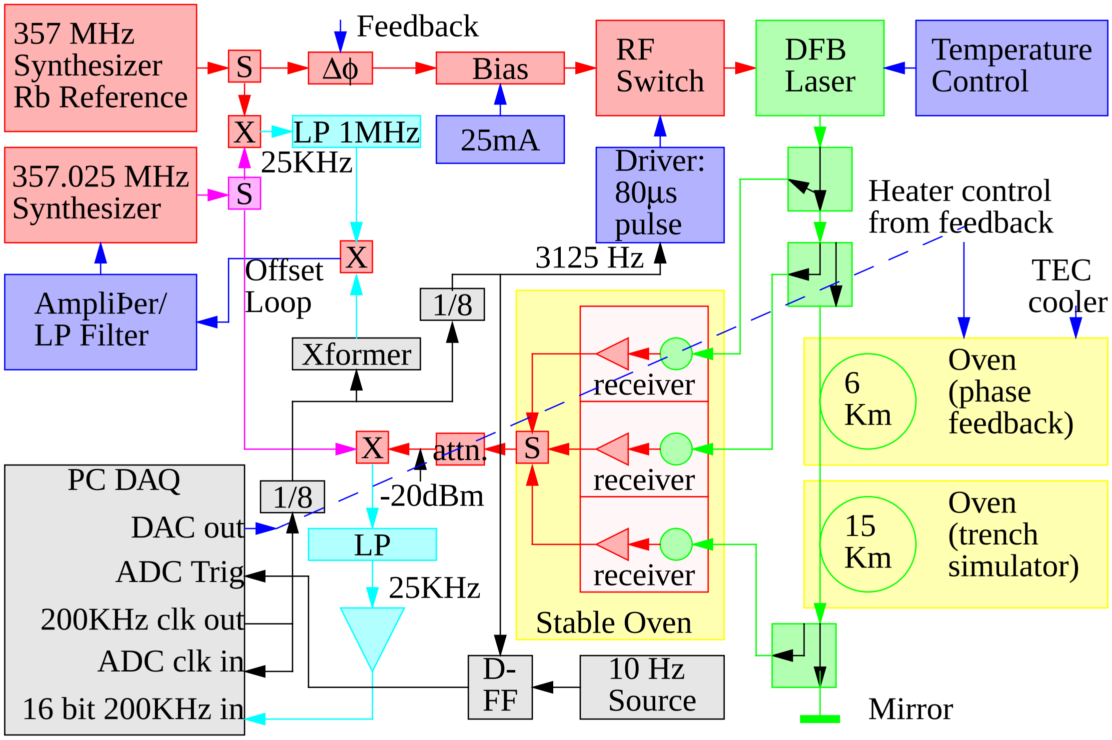

FIGURE 4. A phase test system has been constructed to measure the performance of the feedback.

Test System Performance

The system feedback parameters are still being optimized, however the performance is already adequate. We measure the phase change of the signal at the end of the fiber (with the out going phase subtracted) for a 5°C temperature step on the 15 kilometer fiber. The phase change is less than 2° X-band, which is better than our specification by a factor of 10. Note that with the feedback back off, the step would have been 12,500 degrees X-band. All phases are measured at 357MHz, and then multiplied by 32 to get the X-band phase.

The short term (few seconds) phase noise of the system is 0.2° X-band in a 10Hz bandwidth which meets the requirements. Over moderate time scales there is a phase wander which produces a noise of 1° X-band in a 10Hz bandwidth. We expect that feedback tuning will improve this number.

We are also planning to install a feed forward to improve the noise performance. A RF phase shifter before the diode laser will be adjusted with ½ the phase change seen on the reflected signal. This will to first order correct for any phase wander which is too fast for the temperature feedback system.

The broadband system noise is believed to be due to phase noise in the frequency synthesizer. While it is already acceptable, the noise is expected to be improved by the addition of a low a low phase noise oscillator to replace the synthesizer.

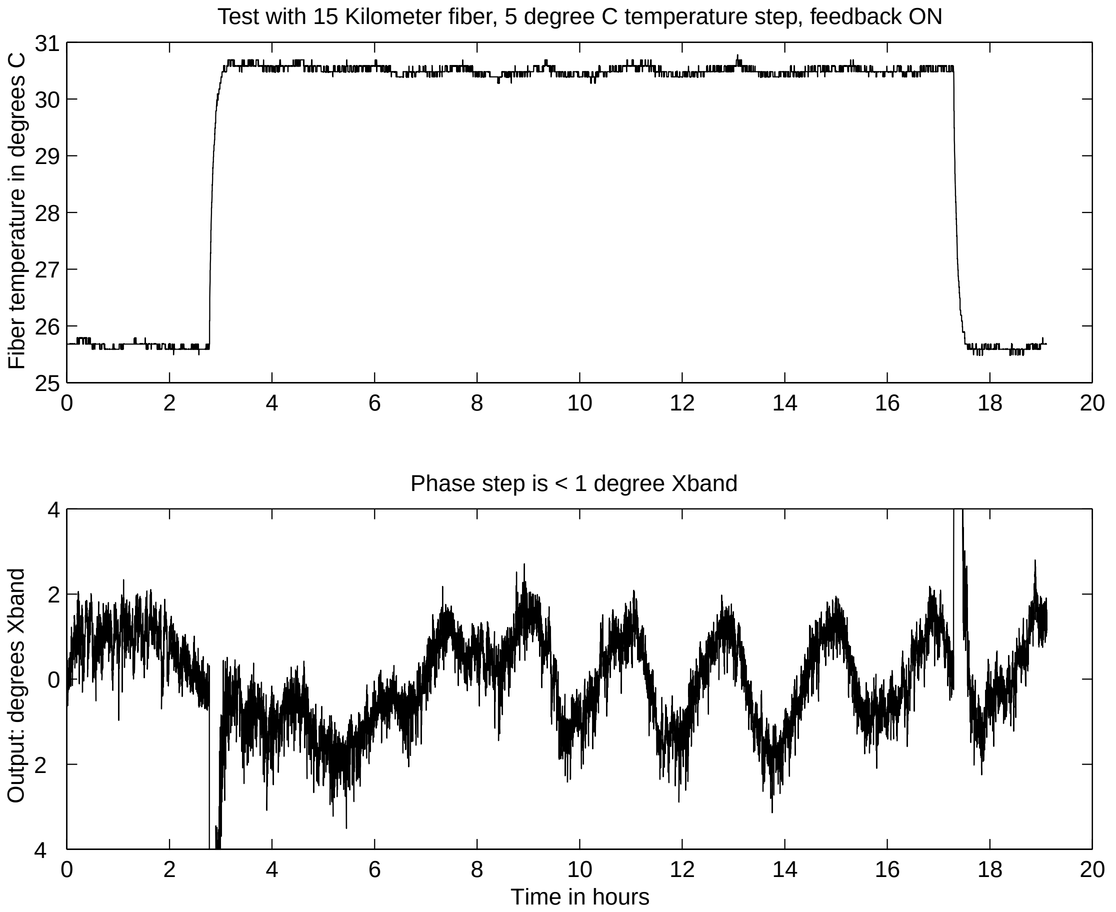

FIGURE 5. Performance of the phase feedback for a 5 degree C temperature step. Phase at end of fiber end is shown with reflected phase stabilized.

Wavelength Tunable Fiber Laser

As an alternate to the extra fiber in a temperature controlled box, were are developing a wavelength tunable fiber laser. The system is required to have a center wavelength of 1550 nm, with 40nm tuning range, and a 0.5 pm tuning step size. The system uses a Erbium fiber laser arranged as an oscillator with an acousto-optical tuner in the feedback loop. Initial testing has provided adequate tuning range and step size, but overall stability is still inadequate.

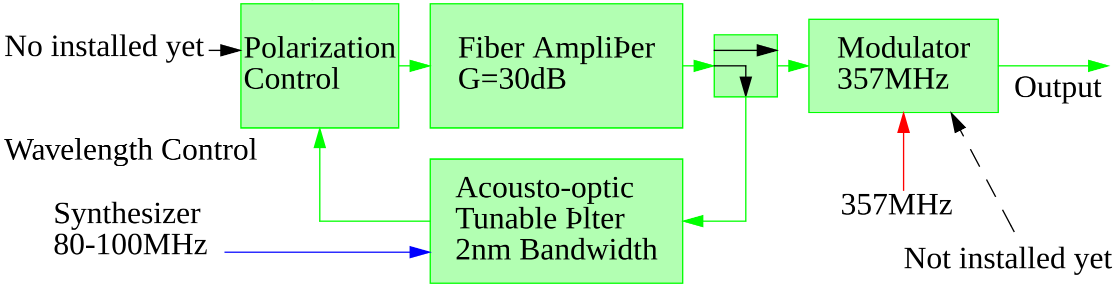

FIGURE 6. Wavelength tunable fiber laser – under development.

BEAM PHASE MEASUREMENT EXPERIMENTS

A system which measures the phase difference between the beam and the Klystron RF was constructed and tested on the SLAC LINAC. The system used a 2846 MHz LO to mix the 2856 MHz RF signal to a 10 MHz IF. This was digitized by a 40 Ms/s digitizer. The accelerator phase reference line was also down mixed and digitized. The Klystron signal from the structure was normally available and its phase was monitored with respect to the phase reference line. On selected pulses, the Klystron was disabled, and the beam induced phase was measured relative to the reference line (which was assumed to have not drifted in phase in 8 milliseconds).

The large signal level difference (40dB) was compensated for with a 40dB switched attenuator. The attenuator phase length was calibrated with a series of switched 10dB attenuators on a 2856 MHz signal derived from the phase reference line. By selecting various combinations of attenuators the overall system consistancy could be checked. Note that the mixer RF levels were set to no more that –15dBm to eliminate amplitude to phase conversion problems.

The system had a measurement noise of 0.3° RMS on a single pulse, and an amplitude to phase conversion of less than 0.3° for 20 dB signal variation. If this performance is maintained when the system is upgraded to X-band it meets the requirements for the single shot (but interrupting) phase measurement. The non interrupting measurement scheme is now being tested with this hardware.

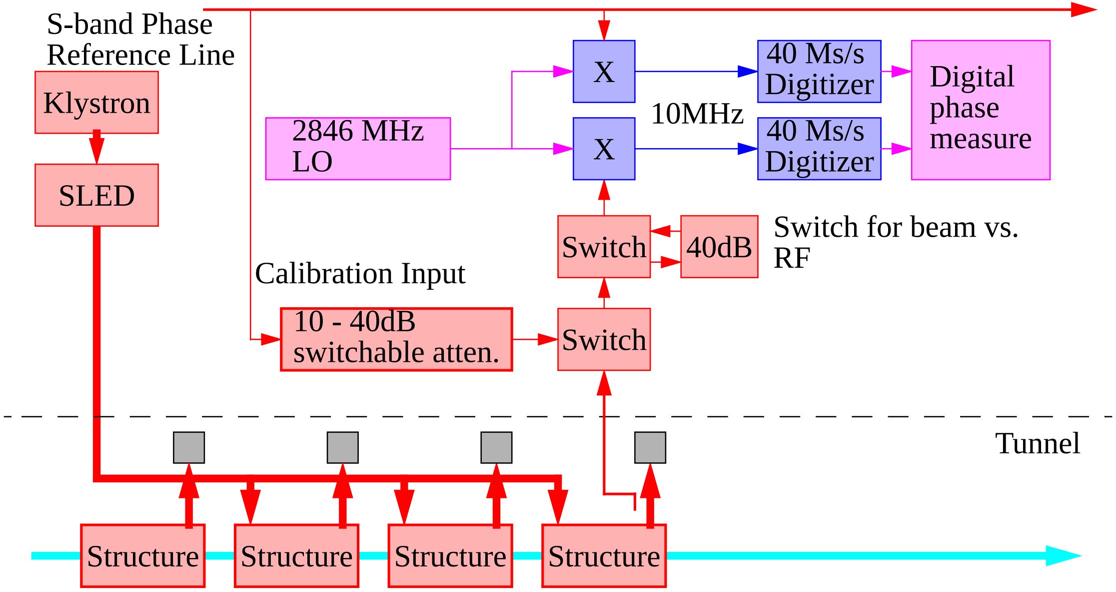

FIGURE 7. Beam phase measurement system – tested on the SLAC LINAC

SUMMARY

Considerable progress has been made on the RF and Timing distribution system for the NLC. All of the critical technical performance requirements have either been met, or will soon be met.