

The NLC RF Phase and Timing Distribution System

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The Next Linear Collider

SLAC / KEK / LLNL / FNAL /..... collaboration

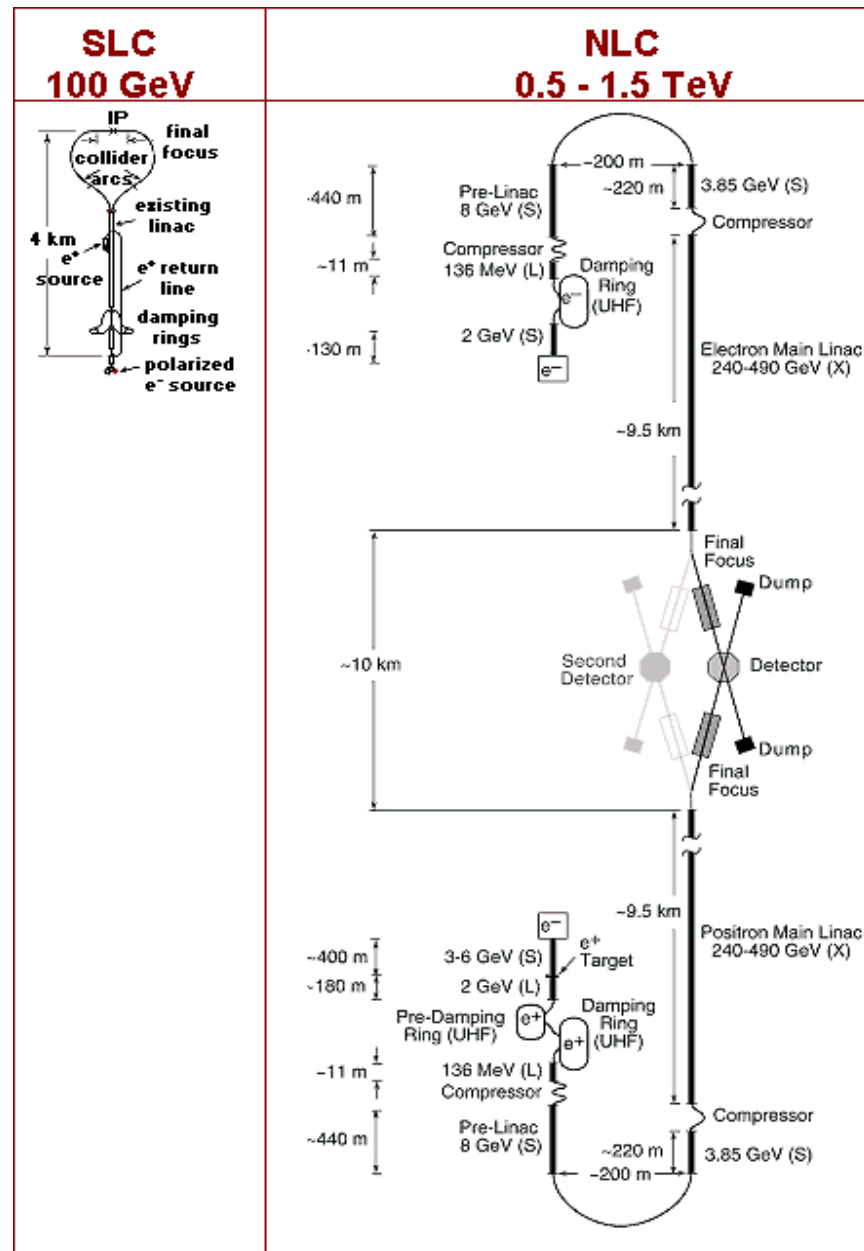
500-1500 GeV Center Mass
 Overall length ~30 kilometers
 Construction in 200X

Two Linacs:

- ~25 “Sectors” per linac.
- ~5000 1.8 meter Structures per linac
- ~1500 Klystrons per linac
- ~190 Modulators / Klystron groups

Phase Requirements

Main Linac X-band 11.424 GHz
 Need $< 1^\circ$ X-band (250fsec)



NLC RF Phase and Timing System

The RF phase requirements are much more stringent than the triggering requirements.

Use low frequency (~500MHz) for phase distribution, and count down timers for triggering.

Similar to the SLAC system

Comparison with other systems.

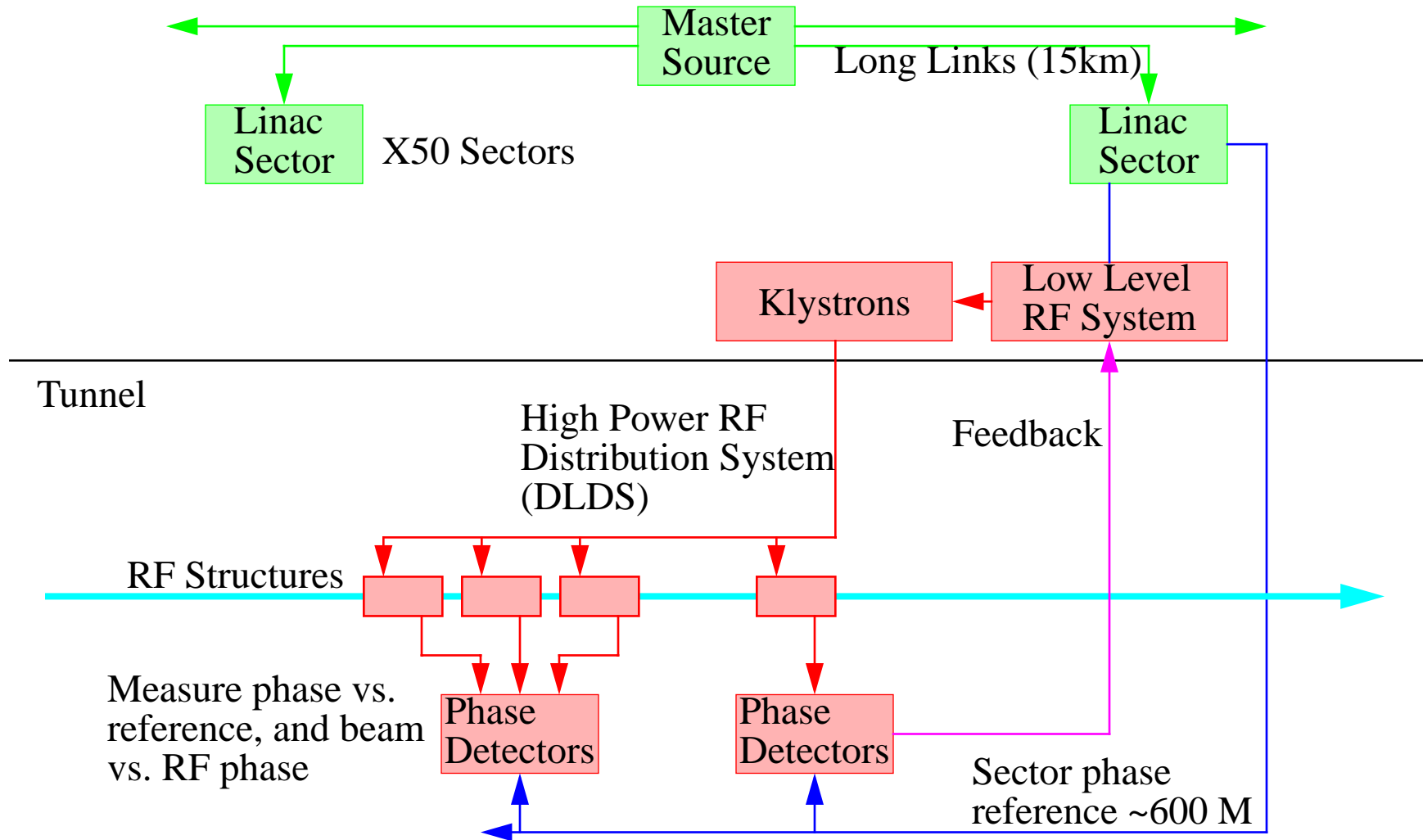
Note: list is from the SNS design review

| Location | NLC (proposed) | SNS (proposed) | SLAC (existing) | CEBAF (existing) | LAMPF (existing) |
|--------------------|---------------------------|--------------------|----------------------|--------------------------|----------------------|
| Length | 30,000 | 540 | 3000 | 185 | 730 |
| Phase stability | 250 fsec | 370 fsec | 10,000 fsec* | 11 fsec (?) | 400fsec |
| $\Delta L/L_{acc}$ | $2.5 \times 10^{-9}^{**}$ | 2×10^{-7} | $1 \times 10^{-6}^*$ | 1.8×10^{-8} (?) | 1.6×10^{-7} |

* With beam feedback, get ~1000 fsec, or 1×10^{-7} stability.

** Open loop (without beam) performance 6000fsec, 5×10^{-8} .

Phase Distribution System Subsystems



Phase distribution system: Sub-systems

Long Links: Need $<1^\circ$ X-band stability over 15 Kilometers for timescales less than beam phase measurement time. Need long term stability $< 20^\circ$ X-band.

Addition requirements for reliability, Machine protection (no single point failure can be allowed to drive the beam into the wall).

System uses phase length stabilized fibers in a point to point distribution system.

Sector Phase Reference: Need $< 1^\circ$ X-band over 600 Meters. System must operate in the tunnel radiation environment (\sim few Rad/hour).

System uses temperature controlled coax, with phase measurement / compensation.

Beam phase measurement: Need to measure beam phase vs. Reference phase to 1° X-band. Need to measure the Beam vs. Klystron RF phase to 1° X-band.

System uses beam induced fields, measured relative to the klystron RF.

Long links - Operating Principle

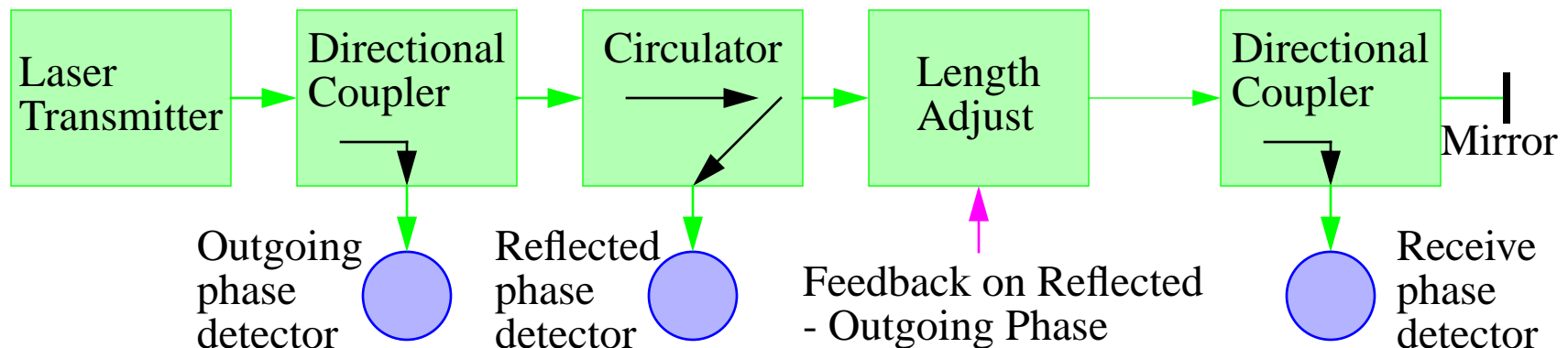
Fiber vs. Coax: Both have similar $\sim 10^{-5}/^{\circ}\text{C}$ temperature coefficients of phase length.

Note that fiber phase length change is dominated by refractive index change with temperature, not physical length change.

Open loop system would require $.005^{\circ}\text{C}$ temperature stability for 20° X-band stability.

Need Feedback

Single mode fiber has much higher length X bandwidth product: Use fiber at 1550nm wavelength to minimize optical loss.



System assumes that changes in outgoing and return phase length are identical

Long Links - Noise

Performance Requirements: We assume that the long links are responsible for the majority of the allowed long term drift ($\sim 20^\circ$ X-band), and 1/3 of the high frequency noise (allow 0.3° X-band from the long links).

Transmission Frequency: Higher frequency reduces noise, Ideally as $f^{1/2}$.

At frequencies above a few GHz, the spectral sidebands from the intensity modulation can destroy the correlation between the forward and reflected phase shifts.

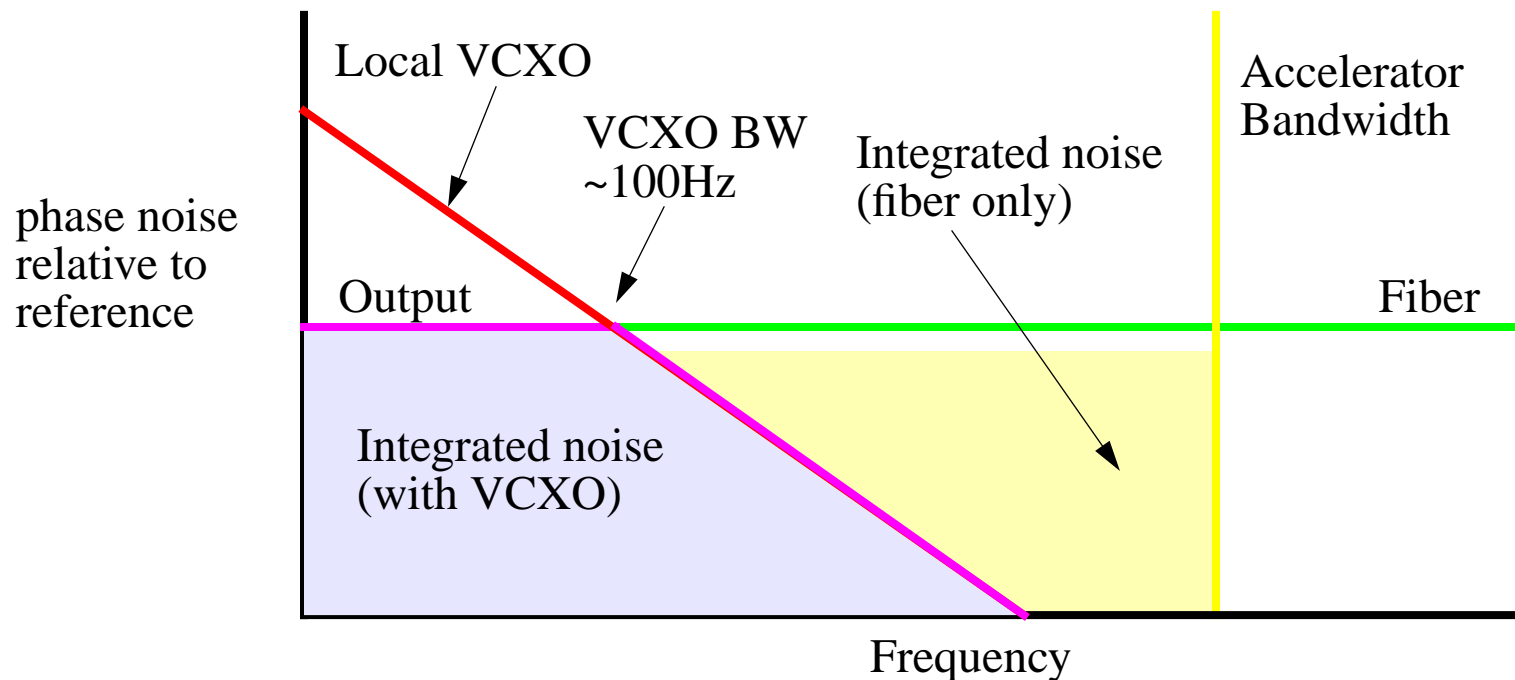
At ~ 500 MHz there is a cost break point. Present system operates at **357MHz** (1/32 of the X-band RF). **Final system frequency will depend on technology.**

In order to measure 0.3° X-band at 357MHz we need 0.01° phase measurement. (tough, but not impossible).

Master Source Phase Noise: Need an integrated phase noise of ~ 76 dBc above ~ 10 KHz (fiber length). **This specification is met by good quality frequency synthesizers.**

Long Links - Noise (continued)

Noise from fiber system is fairly flat over frequency. Need to use a VCXO PLL at the receiver end to bandwidth limit the signal and reduce overall system noise.



PLL VCXO noise requirement: If we assume a VCXO noise power which varies as $1/f^3$ (typical), then we need a noise at 100Hz of $<-93\text{dBc/Hz}$. This requirement is easily met by standard VCXOs. Low noise VCXOs can operate with a bandwidth as low as 10Hz.

Long Links - Noise (continued)

Receiver: Standard telecom receivers in this bandwidth range have $\sim 6\text{pW/Hz}^{1/2}$ noise. If we assume a 100Hz receiver bandwidth (controlled by the PLL), we can operate at received optical powers as low as $\sim 1\mu\text{W}$. (we expect to operate at $\sim 10\mu\text{W}$ on the lowest power receiver.)

Shot Noise: The minimum optical power to obtain the required shot noise is on the order of nanowatts (not an issue).

Transmitter: Need short term wavelength stability $< 5 \times 10^{-4}$ nm, linewidth $< \sim 0.25\text{nm}$. Maximum transmitting power is $\sim 10\text{mw}$, limited by nonlinear frequency conversion (Brillouin scattering).

Transmitter noise requirement: Assuming a 100Hz receiver bandwidth, we need a relative intensity noise of < -95 dBc/Hz RIN. Good DFB diode have RIN < -130 dBc/Hz.

DFB Laser diodes meet our requirements.

We are Also considering a wavelength tunable fiber laser (described later).

Other Sources of Errors

VSWR: Reflections are the bugaboo of most RF length feedback schemes.

We need optical power reflectivities of $< -75\text{dB}$ (assuming coherent reflections), $< -37\text{dB}$ for incoherent reflections.

Typical components (with FC/APC connectors) have $< -55\text{dB}$ return loss. This is sufficient for long runs, but may be an issue for short runs where we can have coherent reflections.

Typical DFB lasers have a linewidth of a few MHz, giving a coherence length of hundreds of meters.

Fortunately, in our system the DFB laser is operated pulsed, and its wavelength sweeps during the pulse. This averages out any coherent effects.

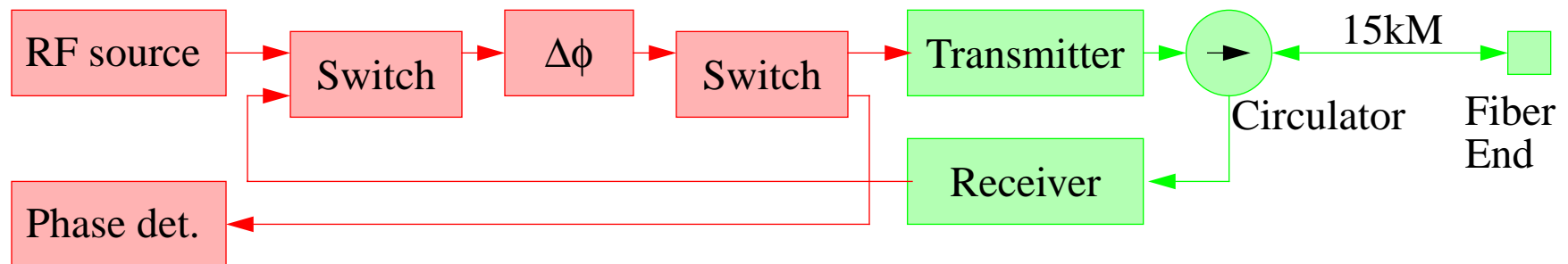
Nonlinearities - Mixers: Tests on mixers indicate that operation at RF levels less than -20dBm reduces nonlinear amplitude to phase conversion to an acceptable level.

Nonlinearities - Other: The detectors, amplifiers, etc. can all be a source of amplitude to phase conversion. We are still studying these issues - but no major problems have been found.

Fiber Length Control Mechanisms (1)

The total length change expected in 15Km for 1°C is 600psec, or 2500°X-band.
Cannot run an open-loop system - would need <0.1% phase accuracy.

Electronic phase shifter: An electronic phase shifter can be placed inside the feedback loop as follows:



Technical issues:

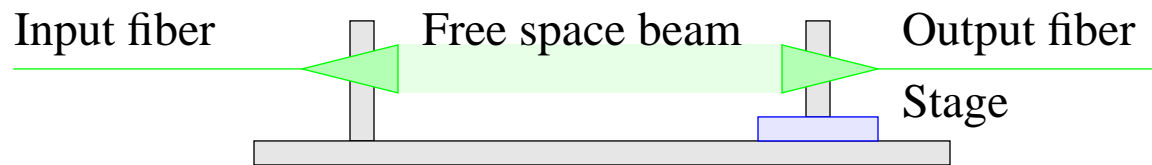
Amplitude sensitivity (non-linearity) of the phase shift of the phase detector may result in different phase shifts for the forward and backward going signals.

The total required phase shift may be impractical for an electronic delay line.

VSWR: Reflections in the RF line may cause unacceptable errors.

Fiber Length Control Mechanisms (2)

Mechanical optical delay line: Mechanical fiber optic delay lines are available with ranges of approximately 300psec. These lines operate by coupling the fiber to free space, and back to fiber, with a precision stage between the two couplers.



Technical issues:

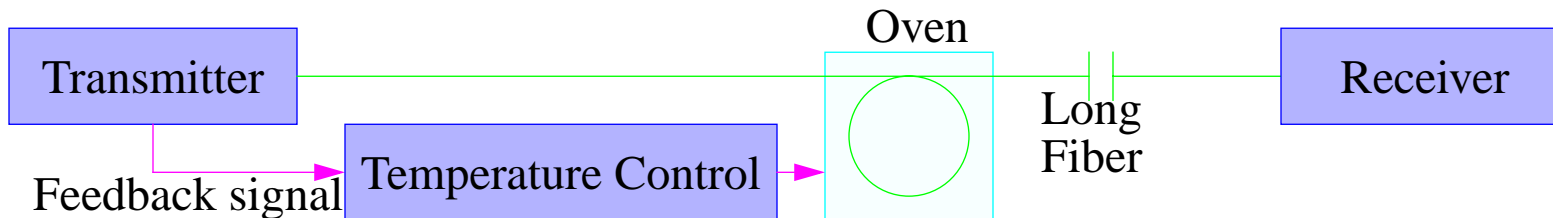
Reflections from free space couplers (VSWR) could produce phase dependent amplitude shifts and non-linearities. Could also produce optical wavelength sensitivities to phase shifts (dramatically increases temperature sensitivity)

Commercial devices have 300psec range, can only compensate for 0.5°C temperature range. Would need a long range device, or good fiber temperature control.

There is concern that the precision mechanical components would not tolerate the continuous operation required for feedback operation.

Fiber Length Control Mechanisms (3)

Temperature controlled additional fiber: A length of fiber, perhaps 50% of the length of the main fiber is installed in series with the main fiber. This fiber temperature is controlled in feedback to compensate for phase changes in the main fiber.



Technical issues:

The slow time response of the oven will complicate the feedback loop

The large number of ovens (~200) will occupy substantial space

This method is used in the present test system

Fiber Length Control Mechanisms (4)

Wavelength / Dispersion length control: The wavelength of the transmitter is adjusted to control the phase length of the fiber through fiber

Fiber dispersion: $\sim 20\text{ps/nm/Km}$.

Fiber temperature coefficient: $40\text{ps/Km/}^\circ\text{C}$

Wavelength range required $\sim 2^\circ\text{nm/}^\circ\text{C}_{\text{fiber}}$

Technical issues:

The transmitter wavelength must be smoothly tunable with a resolution of $5 \times 10^{-4}\text{nm}$ (60MHz optical). This is the most difficult technical challenge.

“Advances” in fiber technology may result in a standard zero-dispersion 1550nm fiber. **This would be incompatible with the dispersion tuning technique.**

On the other hand, **Advances in DWDM (dense wavelength division multiplexing) fiber transmission system are pushing the development of tunable laser which meet our specs.**

Meanwhile: We are developing our own tunable laser system. (discussed later)

Test System

Test Fiber Length: 15 Kilometers in temperature controlled oven.

Frequency: 357MHz

Transmitter: DFB laser diode, 1mw at 1550nm

Phase Detection:

Pulse diode on for $\sim 50\mu\text{s}$ ($<$ fiber length)

Combine detected signals. Three detector signals now “time multiplexed”.

Mix received signals down to 25KHz.

Digitize 25KHz IF at 200KHz, 16 bits (12 effective bits).

Fit sine and cosine (digital phase detection).

Data Acquisition cycle of 10Hz. Approximately 50% of time used for acquisition.

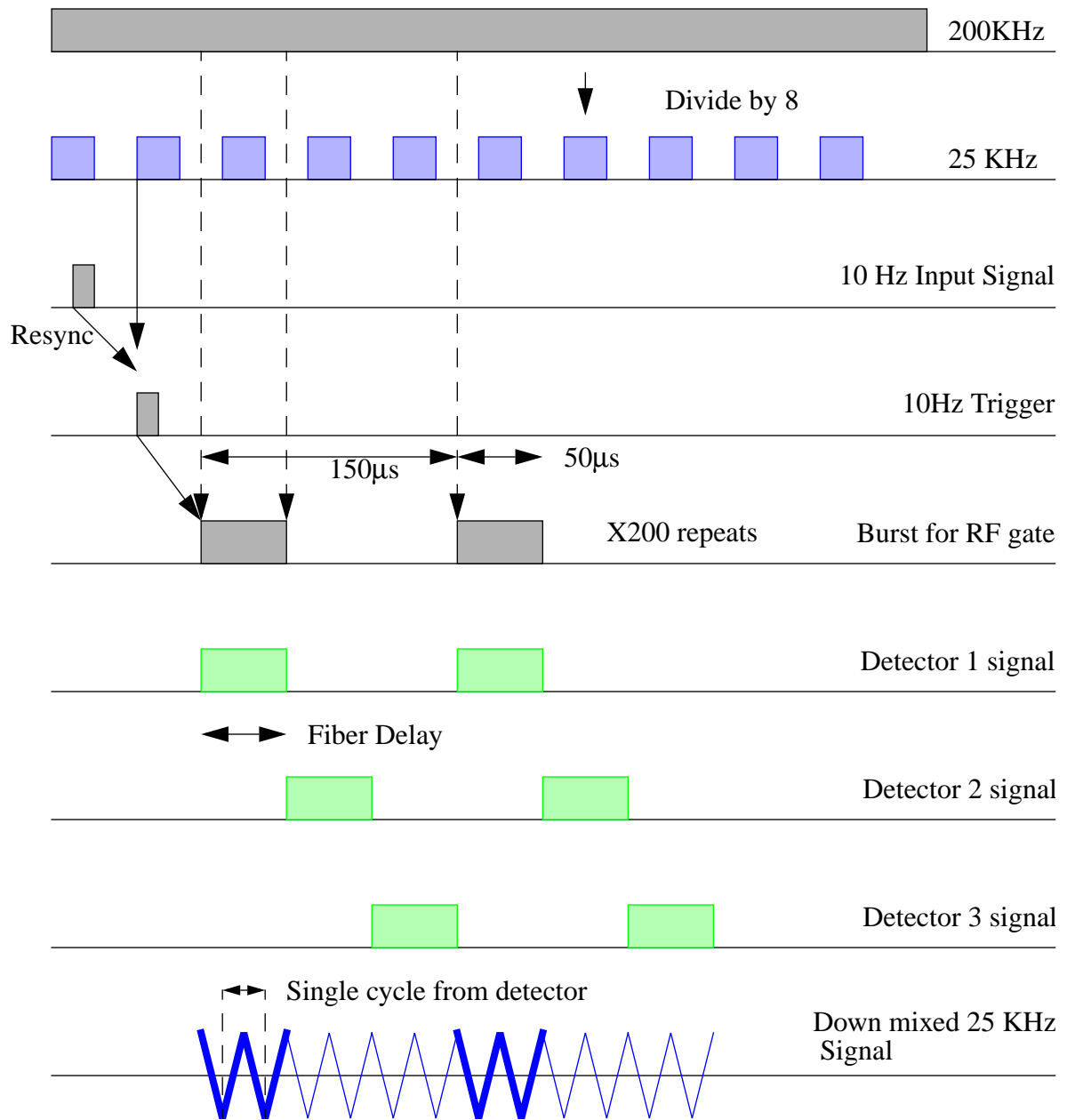
Length Adjust:

Use external oven with 2.2Kilometers of fiber, range $\sim 10^0$ C.

Oven uses a constant heater with variable rate fan cooling fiber for fast response.

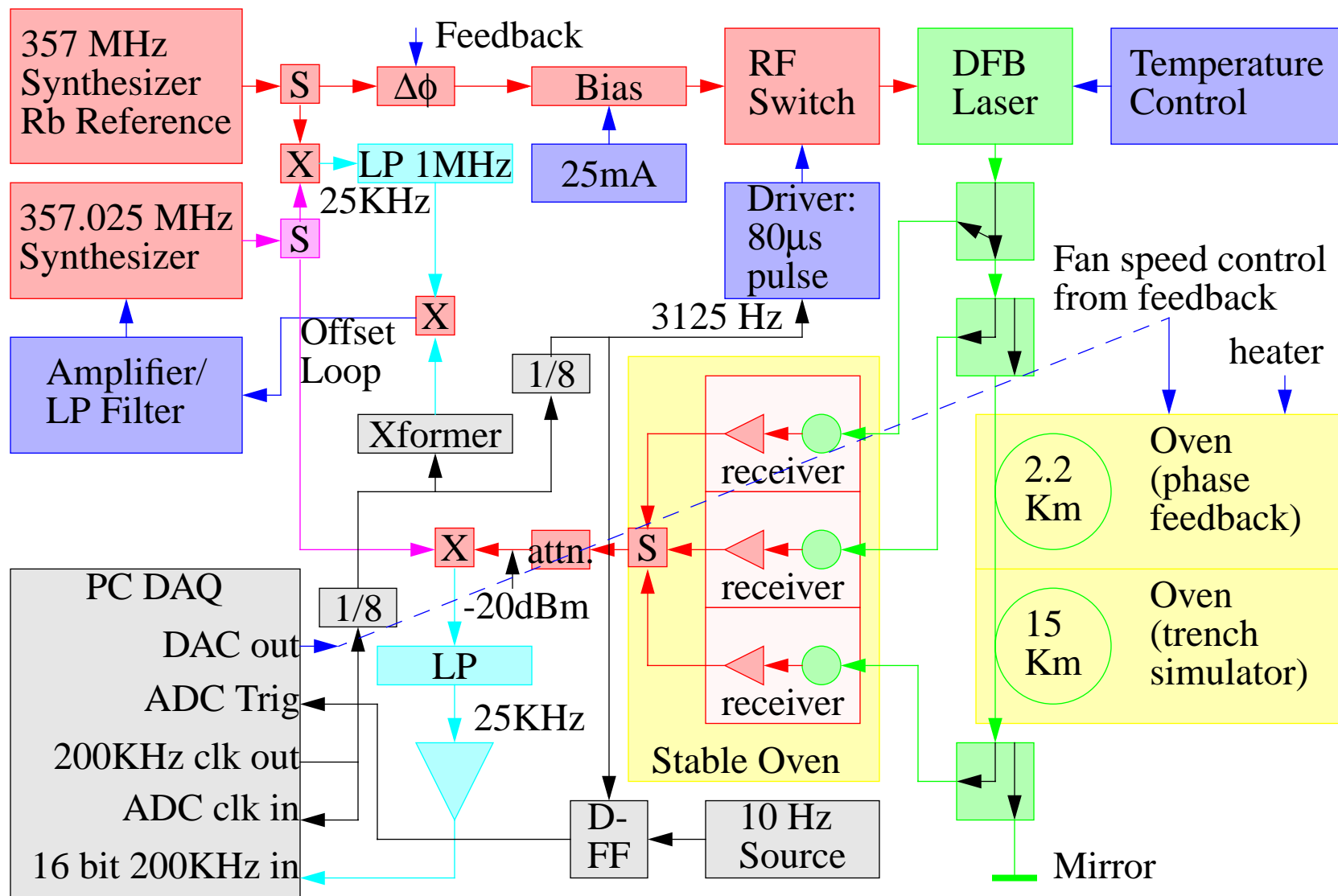
Oven with TEC cooler to increase temperature range is under construction

Note: 2.2 Kilometer fiber was available. 7 kilometer fiber is on order.



Entire cycle repeats at 10Hz. Note that burst spacing is determined by fiber length.

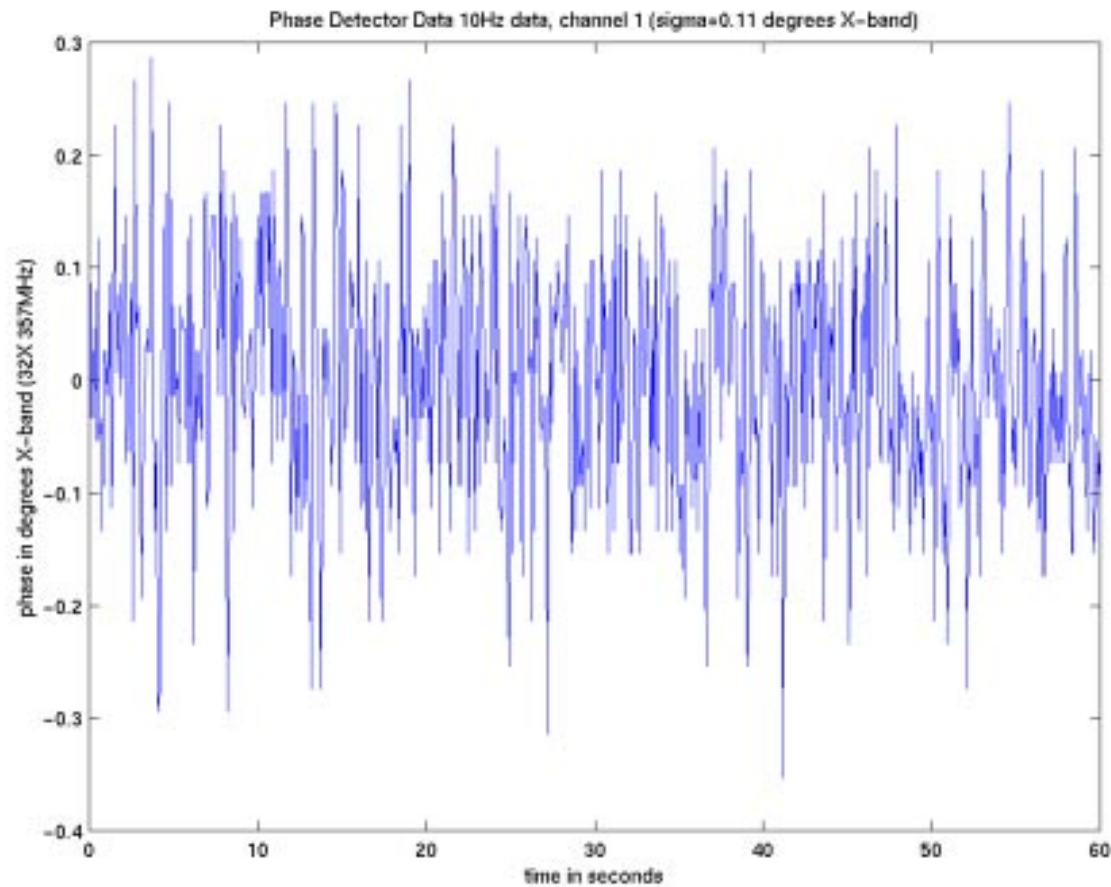
Test System - Block Diagram





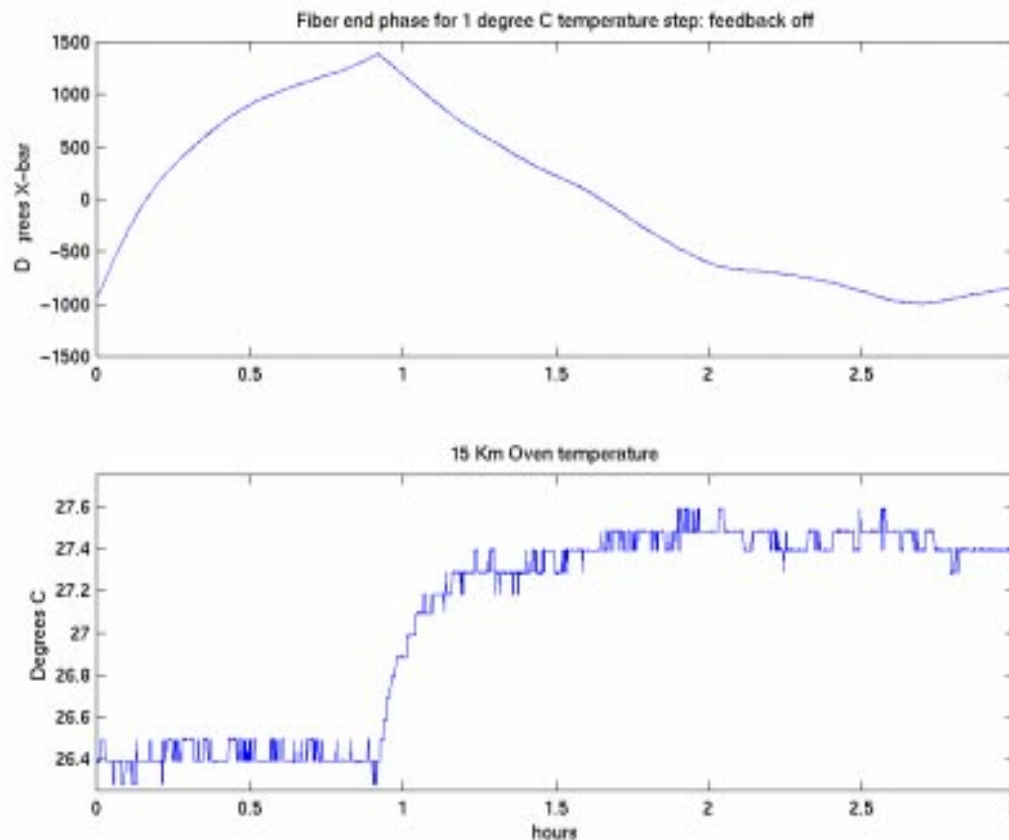
Test System - Electronics performance (no fibers)

For this test, the output of the RF switch was attenuated and fed into the mixer. Noise (measured at 10 Hz) was 0.11° X-band (meets our spec).



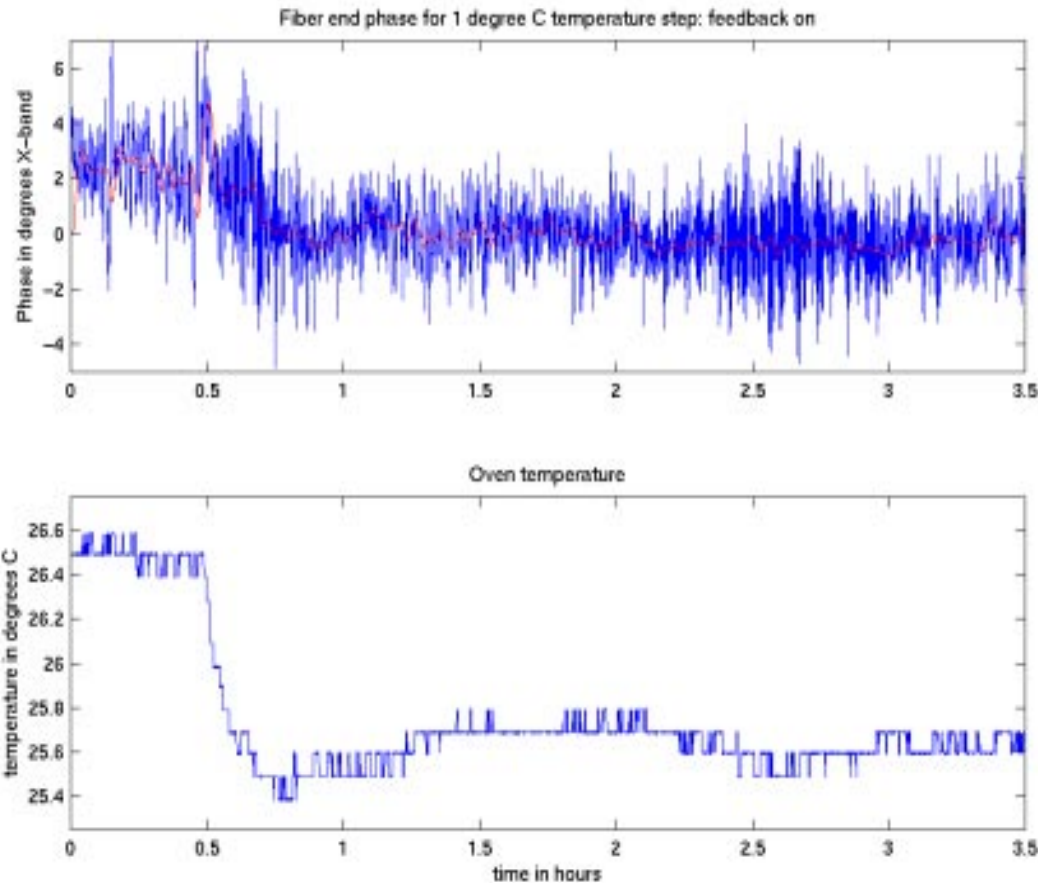
Test system performance - open loop

The temperature coefficient phase for fused silica fiber results from the expansion coefficient $5 \times 10^{-7}/^{\circ}\text{C}$ (small), and the index change $\sim 10^{-5}/^{\circ}\text{C}$ (dominates). For a 15Km fiber, we expect a phase sensitivity of $2800^{\circ}\text{X-band}/^{\circ}\text{C}$. We observe $\sim 2200^{\circ}\text{X-band}/^{\circ}\text{C}$.



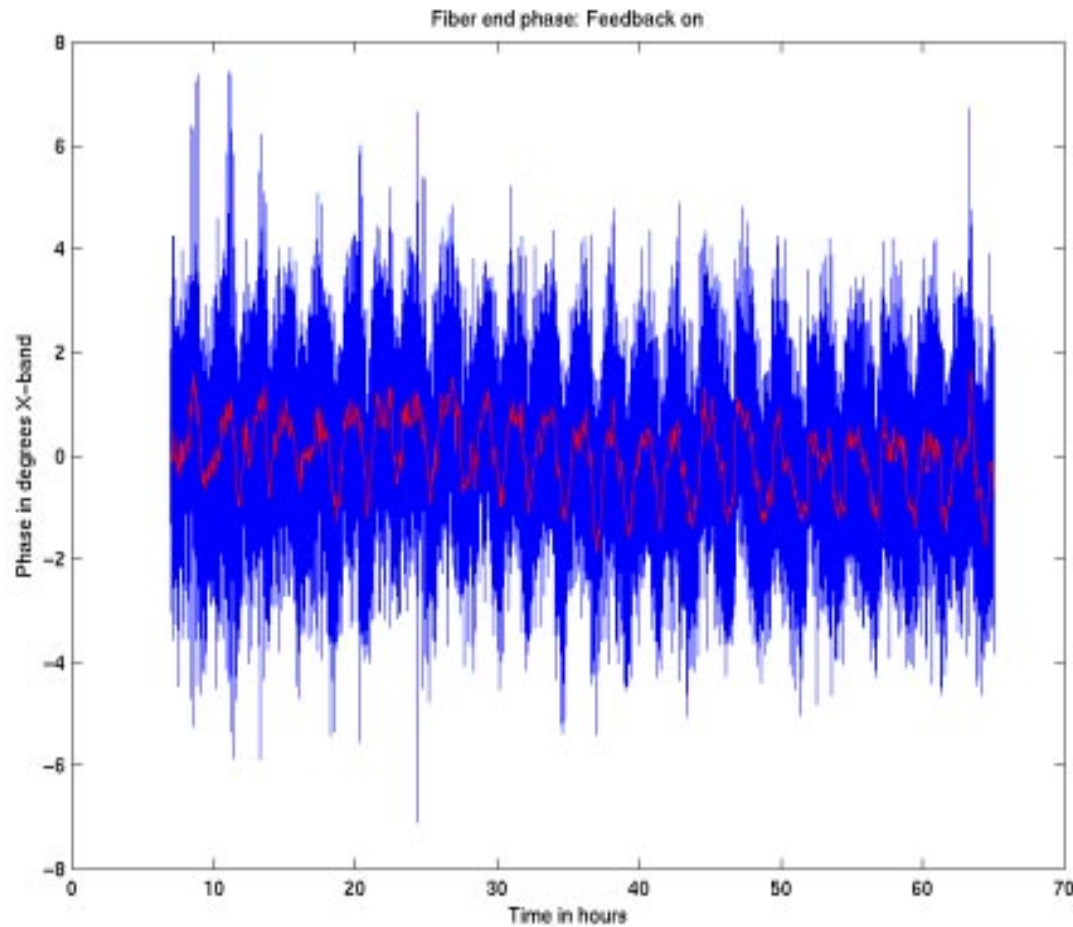
Test System Performance - Closed Loop

With the feedback on, the reflected phase signal shows no variation (other than broadband noise). The Feedback oven temperature is controlled. Output shows $\sim 3^\circ\text{X-band}/^\circ\text{C}$. (Factor of 700 improvement)



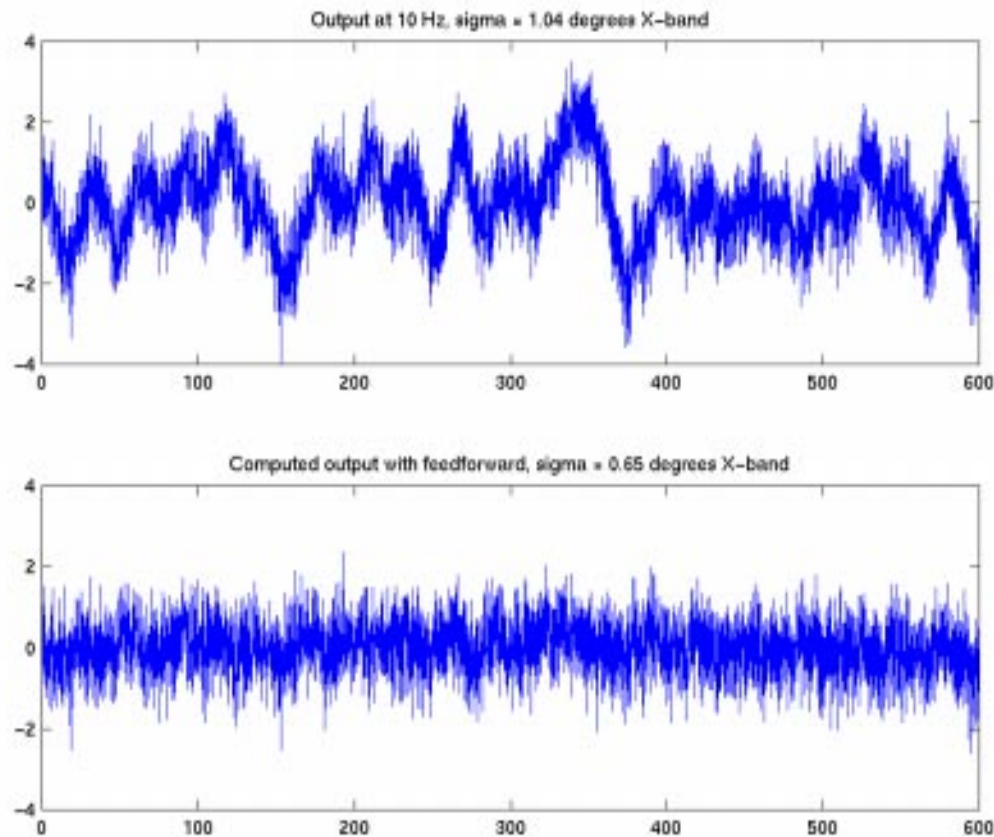
Phase stability for a 3 day run.

A 3 day run with the 15Km fiber oven temperature constant (to $<0.1^{\circ}\text{C}$) was done to look at the long term stability. Note that the deviation of the output is $\sim 1.4^{\circ}$ X-band RMS.



Test System Noise - 10 Hz data.

For a run with 10 Hz data recording, we see 1° X-band noise on the fiber output. If we calculate the expected response of a phase feedforward the noise would be 0.65° X-band (in a 10Hz bandwidth).



Long Fiber Link System: Present Status

| Parameter | NLC System | Test System - measured |
|-------------------------------|---|----------------------------|
| Transmission distance | 1 to 15 Kilometers | 15 Kilometers |
| Fiber temperature range | +/- 5°C* | +/- 1°C |
| Long term phase stability | +/- 20° X-band | +/- 3° X-band (3 day test) |
| Phase temperature coefficient | < 4° X-band / °C* | <3° X-band / °C |
| Phase Noise | <0.3° X-band, 10Hz BW <0.3° at 100 Hz desired. | 1° X-band, 10 Hz BW** |

*Based on SLAC summer / winter temperatures and 1 Meter burial depth

**0.6° X-band predicted with feedforward.

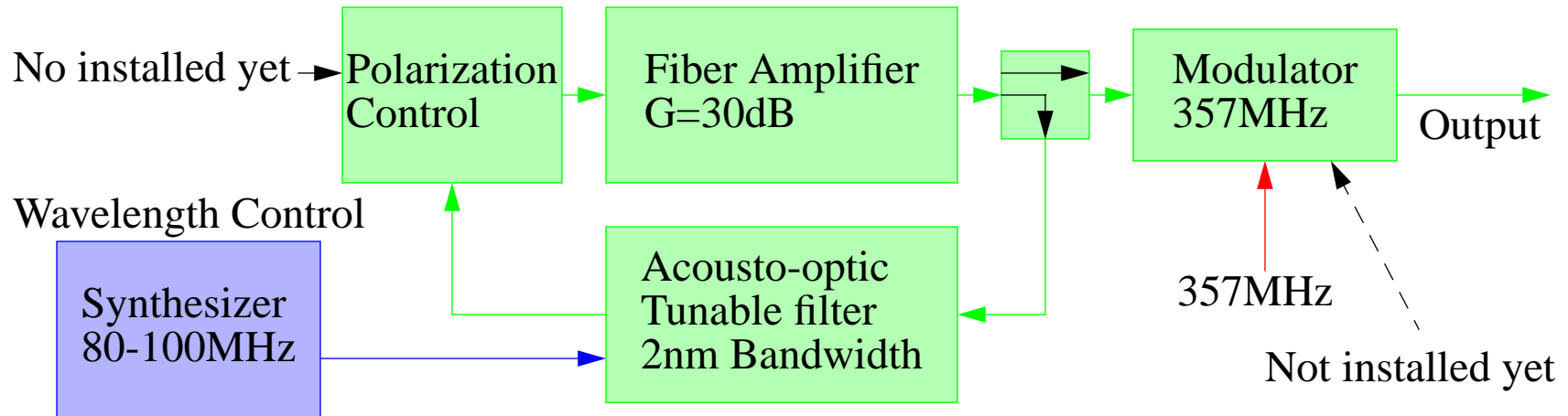
Fiber temperature range: Will use longer (7 Kilometer) control fiber and thermo-electric cooler in oven for increased temperature range.

Phase Noise: Investigating lower noise DFB laser, lower noise receivers, low phase noise master source.

Long Link Fiber System - Wavelength Tunable Laser

An alternate length control method is to use a wavelength tunable laser which couples with the fiber dispersion to change the effective fiber length. **Eliminate Ovens**

Standard tunable lasers either have excessive step sizes, or use moving mechanical components which are unsuitable for continuous feedback operation. We are developing a wavelength tunable fiber laser:



| Parameter | Requirement | Demonstrated |
|----------------------|---------------|--------------------------|
| Tuning Range | 40nm | 50nm |
| Wavelength step size | <0.5pm | <1pm (measurement limit) |
| Noise | -95dBc/Hz RIN | Not measured |

Sector Phase Reference

This system distributes the phase from the long fiber links throughout a ~600M sector. The stability and noise requirements are similar to those for the long links: $\sim 0.3^\circ$ X-band.

Technical issues: (why is this hard?)

System has many pick-offs (~ 100), point to point links are not practical.

Some signals needed in the accelerator tunnel: radiation environment (~ 1 Rad/hour), fibers not suitable.

Need stability 0.3° X-band / 600M. = 3×10^{-7} .

Planned Solution

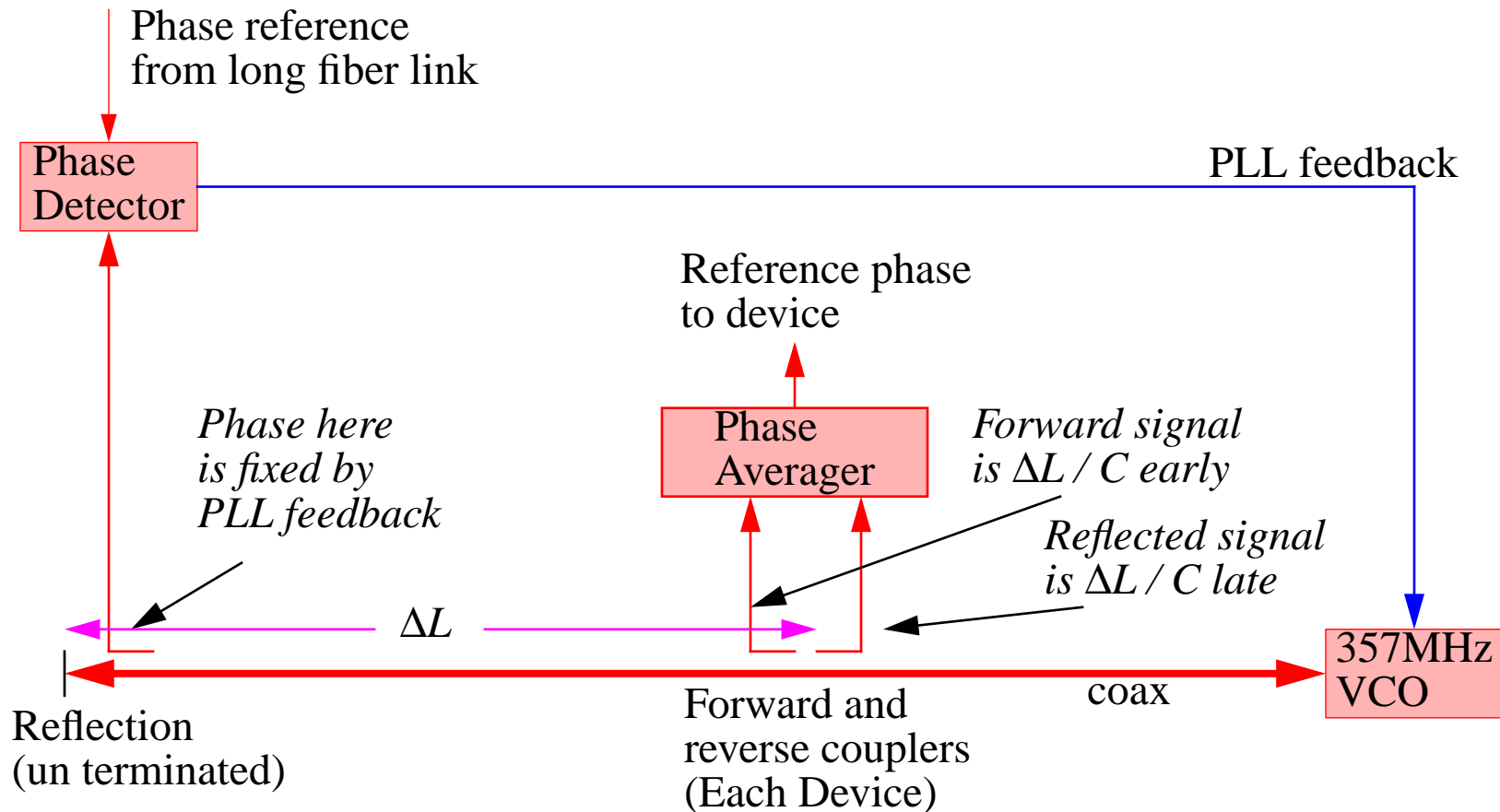
Can we use temperature stabilized lines?

Temperature coefficient of copper is $\sim 10^{-5}/^\circ\text{C}$. Would need $.03^\circ\text{C}$ stability (very hard).

Instead use good temperature stability 0.3°C (SLAC accelerator water meets this spec), and Feed Forward.

Sector Phase Reference Feedforward Scheme

(Originally from Keith Jobe)

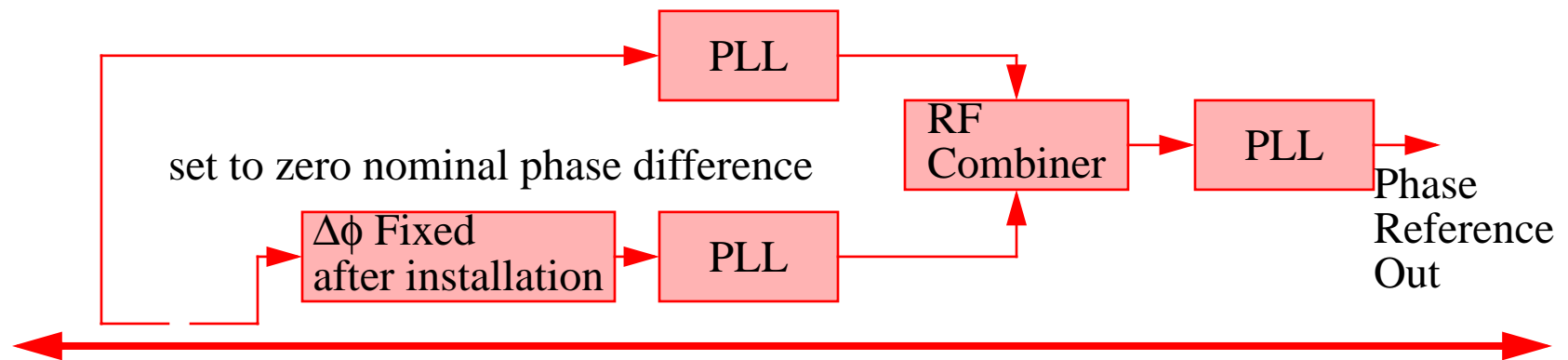


Ideally system corrects exactly for length changes for all devices.

VSWR will reduce system accuracy - not yet calculated or tested.

Sector Phase Reference: Phase Averager

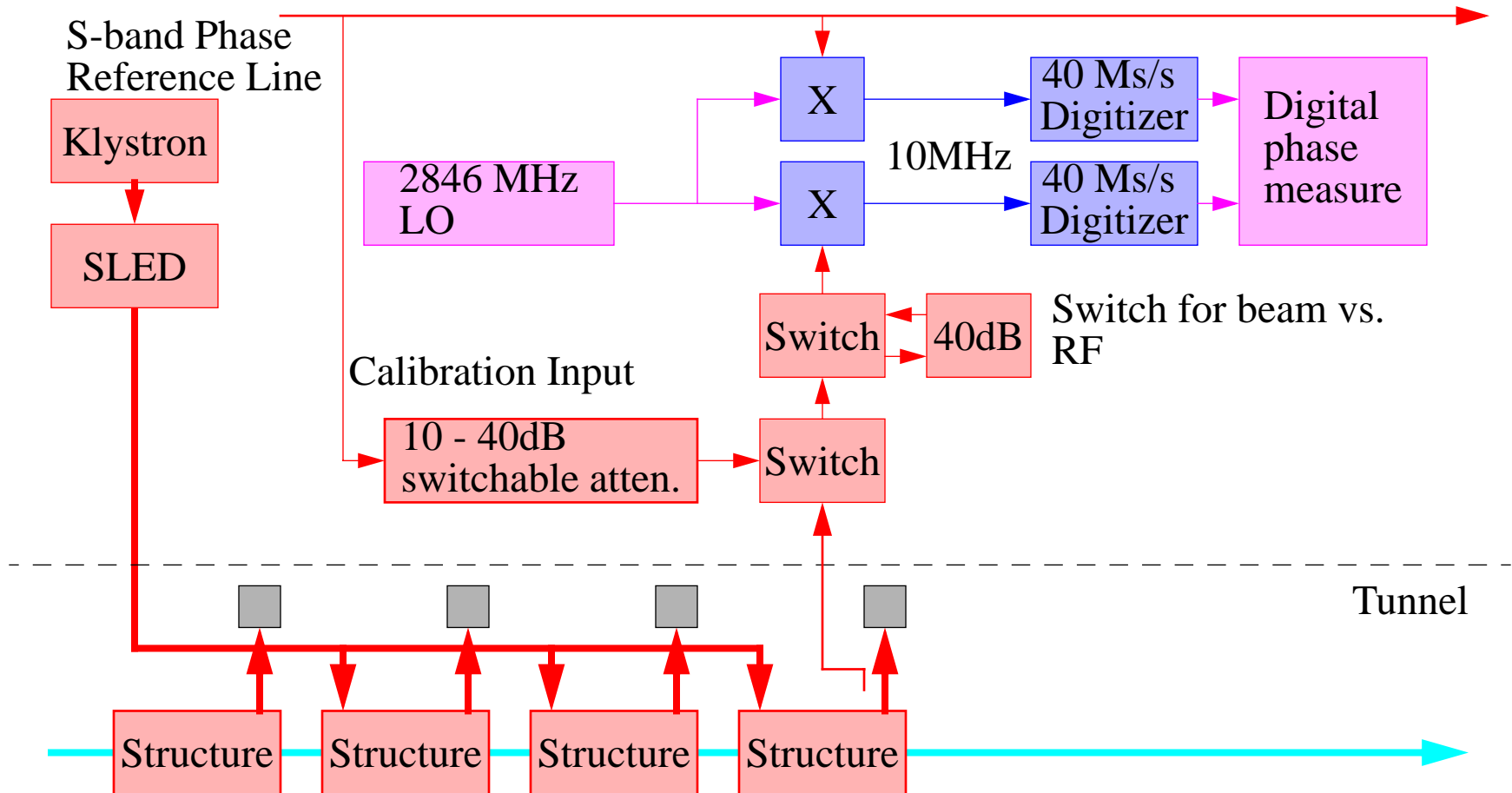
Phase changes are small: $\sim 0.1^\circ$ 357 MHz (3° X-band) if we have good temperature stability. **Can use linear system**



We will construct a prototype to test the performance of this scheme.

Beam Phase Measurement

The beam phase can be measured relative to the klystron RF by looking at the beam induce fields in the accelerator structures.



Beam Phase Measurement: Results of Initial Tests

System was used to alternately measure the beam induced fields with the RF off, and the accelerating fields with the RF on.

Initial tests done at S-band (2856MHz) on the SLC linac.

| | |
|------------------------------------|--|
| Measurement noise (single pulse) | 0.3° S-band RMS (calibration channel) |
| Measurement linearity | <0.3° S-band for 20dB signal variation |
| Measured drift of SLAC beam vs. RF | +/- 2° S-band over 10 Hours. |

The RF signal level on the mixers was limited to -15dBm to limit nonlinear amplitude to phase conversion. Improved mixers should allow ~10dB improvement in noise. (~-.1° phase measurement on a single pulse).

Paul Corredoura has a scheme with signal averaging where the beam phase is detected in the presence of the accelerating fields. System to be tested in the next few months.

Laser Pulse Timing: Noise Estimate

The beam phase detection test system has already measured bunches with a noise of 0.3° S-band, corresponding to 300 fsec. The system noise is not dependant on frequency, and should be similar for X-band. If we assume the use of higher power mixers (to be tested soon), we should be able to measure single bunch timings to **25 femtoseconds**.

A typical 12GHz laser detector has a noise of $30\text{pw}/\text{Hz}^{1/2}$, and a maximum signal of 100mW. On a single shot measurement, with 12GHz bandwidth, this corresponds to a signal to noise of 3×10^4 , corresponding to a phase measurement of 0.002 degrees, or about **0.5 femtoseconds**. (obviously something else will limit us above this level).

Since the laser beam is measured at a different location from the electron beam, it will be necessary to use a system similar to the *Sector Phase Reference* (described earlier) to move the timing reference between the two. We expect noise in the $\sim 0.1^\circ$ X-band level.

Overall: Laser pulse timing measurements at the ~ 50 femtosecond level should be possible.

Phase and Timing Distribution Summary

A variety of systems, including the NLC and 4th generation light sources required phase and timing distribution at the ~ 100 femtosecond level.

A prototype system for the NLC has demonstrated 0.5 to 2 picosecond long term timing stability over 15 Kilometers.

The prototype has short term ($< \text{hour}$) noise of 170 femtoseconds over 15 Kilometers.

Work is progressing on an intermediate length (600Meters), multi-tap system.

A beam phase monitor has demonstrated 0.3° S-band noise on the SLC beam. Improvements are expected to provide 0.1° X-band (25 femtosecond) single bunch measurements.

It should be possible to measure the timing of single laser bunches with respect to the electron beam at the 50 femtosecond level.