

NLCTA-Note #16

February 3, 1994

Subject: SLED-II Delay-Line Length Stabilization

Authors: T. L. Lavine, C. D. Nantista,
and Z. D. Farkas

Contents

1. Introduction
2. Symbolic Definitions and Nominal Values
3. Thermal Expansion of the Phase Length of a Delay Line
4. Analysis of SLED-II with Delay-Line Length Errors
5. An Algorithm for Fine-Tuning the Delay-Line Lengths
6. Precision and Duty Cycle of Tuning Sensors and Actuators

1. Introduction

In this note we analyze the effect on a SLED-II pulse compressor of errors in the lengths of the delay lines in the NLC Test Accelerator design. The length of each of the two delay lines is supposed to be an integer number of half wavelengths (between the reflecting iris and the shorted end), making each delay line resonant. Thermal expansion and contraction, or misadjustment of the adjustable shorting plungers, may cause the delay line lengths to differ from the nominal length, which will affect adversely the amplitude and phase of the SLED-II output pulse. Since the length errors of the two delay lines may differ from one another, we have evaluated both common and differential error modes. We discuss a feedforward tuning algorithm for stabilizing the delay line lengths, and we derive tolerances on the sensors and control actuators necessary to implement it.

2. Symbolic Definitions and Nominal Values

We will use the following symbolic definitions and nominal values from the NLC Test Accelerator design:

| | |
|--|---|
| Pulse-compression ratio | $N = 6$ |
| Round-trip delay-line transit time | $\Delta t = 250 \text{ ns}$ |
| Delay-line length | $L = 120' = 36.6 \text{ m}$ |
| Delay-line waveguide (WC475) radius | $a = 4.75''/2 = 0.0603 \text{ m}$ |
| Round-trip field attenuation of each delay line | $e^{-2\tau} = 0.99$ |
| Reflection coefficient of each delay line's iris | $s = 0.684$ |
| Wavenumber in free-space | $k_0 = 2\pi/(2.62 \text{ cm})$ |
| Wavenumber in WC475 delay line | $k_g = 2\pi/(2.72 \text{ cm})$ |
| Linear thermal expansion coefficient | $\kappa = 16.8 \times 10^{-6} / ^\circ\text{C}$ |
| Average temperature change of a delay line | ΔT |
| Length changes of the two delay lines | $\Delta L_1, \Delta L_2$ |
| Phase-length changes of the two delay lines | ϕ_1, ϕ_2 |
| E -field from klystron | $\mathbf{E}_0 = E_0 e^{j\omega t}$ |
| E -field emitted from iris of ℓ th delay line during n th time interval of duration Δt | $\mathbf{E}_{e,\ell}^{(n)} = E_{e,\ell}^{(n)} e^{j\omega t}; n = 1, \dots, N$ |
| E -field of output pulse during n th time interval of duration Δt | $\mathbf{E}_{out}^{(n)} = E_{out}^{(n)} e^{j\omega t}$ |
| E -field reflected back to klystron during n th time interval of duration Δt | $\mathbf{E}_r^{(n)} = E_r^{(n)} e^{j\omega t}; n = 1, \dots, N$ |
| E -field of compressed pulse | $\mathbf{E}_c = \mathbf{E}_{out}^{(n=N)}$ |
| Rf phase shift of compressed pulse due to delay-line length errors | $\Delta\theta$ |

3. Thermal Expansion of the Phase Length of a Delay Line

Thermal expansion modifies both the length L and radius a of a delay line by

$$\Delta L = \kappa \Delta T L$$

and

$$\Delta a = \kappa \Delta T a.$$

Since the wavenumber in the delay line waveguide is

$$k_g = k_0 \sqrt{1 - (3.832/k_0 a)^2},$$

the phase angle $k_g L$ is modified to

$$\begin{aligned} (k_g + \Delta k_g)(L + \Delta L) &= k_0 \sqrt{1 - [3.832/k_0(a + \Delta a)]^2} (L + \Delta L) \\ &\approx k_g L [1 + \kappa \Delta T (k_0/k_g)^2], \end{aligned}$$

so the change in the round-trip phase length of a delay line is

$$\phi = 2[(k_g + \Delta k_g)(L + \Delta L) - k_g L] \approx 2k_g L \kappa \Delta T (k_0/k_g)^2.$$

An effective length change, ΔL^* , can be defined that includes the effect of thermal expansion of radius with length:

$$\Delta L^* = \phi/2k_g = L \kappa \Delta T (k_0/k_g)^2.$$

In the limit of large waveguide radius ($k_0 a \gg 3.832$), $k_g \rightarrow k_0$ and $\Delta L^* \rightarrow \kappa \Delta T L$, as expected. The 4.75-inch diameter of the delay lines is fairly large ($k_0 a = 14.4$) and the factor k_0/k_g is 1.037.

The relationships between phase length, effective physical length, and temperature can be summarized as

$$\phi = \frac{\Delta L^*}{0.217 \text{ cm}} = \frac{\Delta L^*}{0.0853 \text{ inch}} = \frac{\Delta T}{3.28^\circ \text{C}}$$

and

$$\frac{\Delta L^*}{\Delta T} = 0.0661 \text{ cm}/^\circ \text{C} = 0.0260 \text{ inch}/^\circ \text{C}. \quad (1)$$

4. Analysis of SLED-II with Delay-Line Length Errors

Delay-line phase-length errors (ϕ_ℓ where $\ell = 1, 2$) will detune the nominally resonant delay lines. The effect of the detuning can be analyzed by adding to the standard SLED-II analysis¹ an imaginary counterpart to the attenuation parameter.² We will assume that the length errors are on the scale of an rf wavelength so that the output pulse length, which is the round-trip transit time, is negligibly affected. Under these assumptions, the electric field amplitude emitted from the ℓ th delay line during the n th time interval of length Δt is given by

$$E_{e,\ell}^{(n)} = \frac{1-s^2}{\sqrt{2}} e^{-2\tau+j\phi_\ell} [1 + se^{-2\tau+j\phi_\ell} + \dots + (se^{-2\tau+j\phi_\ell})^{n-2}] E_0, \text{ for } n \geq 2, \quad (2)$$

$$E_{e,\ell}^{(1)} = 0, \text{ for } n = 1,$$

which, in the limit of infinitely many round-trip transit time intervals, becomes

$$\lim_{n \rightarrow \infty} E_{e,\ell}^{(n)} = E_{e,\ell}^{(\infty)} = \frac{1-s^2}{\sqrt{2}} \frac{e^{-2\tau+j\phi_\ell}}{1-se^{-2\tau+j\phi_\ell}} E_0. \quad (3)$$

Expression (3) can be used to rewrite expression (2) in closed form:

$$E_{e,\ell}^{(n)} = [1 - (se^{-2\tau+j\phi_\ell})^{n-1}] E_{e,\ell}^{(\infty)} = \frac{1-s^2}{\sqrt{2}} \frac{1 - (se^{-2\tau+j\phi_\ell})^{n-1}}{1 - se^{-2\tau+j\phi_\ell}} e^{-2\tau+j\phi_\ell} E_0.$$

In nominal SLED-II operation, the phase of the klystron pulse is reversed at time $t = (N-1)\Delta t$, after the delay lines have been filled for $N-1$ time intervals. During the N th

interval, the field amplitude seen at the output is $\frac{1}{\sqrt{2}}$ times the sum of the amplitudes emitted by the delay lines plus the reflection (with coefficient s) from the irises of the klystron wave amplitude. These amplitudes add constructively in the absence of line-length errors. The electric field amplitude of the SLED-II output (compressed) pulse during the N th time interval of duration Δt is

$$\begin{aligned}
E_c = E_{out}^{(N)} &= \frac{1}{\sqrt{2}} [E_{e,1}^{(N)} + E_{e,2}^{(N)}] + sE_0 \\
&= \frac{(1-s^2)e^{-2\tau}}{2} \left[\frac{1 - (se^{-2\tau+j\phi_1})^{N-1}}{1 - se^{-2\tau+j\phi_1}} e^{j\phi_1} \right. \\
&\quad \left. + \frac{1 - (se^{-2\tau+j\phi_2})^{N-1}}{1 - se^{-2\tau+j\phi_2}} e^{j\phi_2} \right] E_0 + sE_0.
\end{aligned} \tag{4}$$

The electric field amplitude reflected back toward the klystron through the hybrid during the N th time interval of duration Δt is

$$\begin{aligned}
E_r^{(N)} &= \frac{1}{\sqrt{2}} [E_{e,1}^{(N)} - E_{e,2}^{(N)}] \\
&= \frac{(1-s^2)e^{-2\tau}}{2} \left[\frac{1 - (se^{-2\tau+j\phi_1})^{N-1}}{1 - se^{-2\tau+j\phi_1}} e^{j\phi_1} \right. \\
&\quad \left. - \frac{1 - (se^{-2\tau+j\phi_2})^{N-1}}{1 - se^{-2\tau+j\phi_2}} e^{j\phi_2} \right] E_0.
\end{aligned} \tag{5}$$

One can define common and differential error modes which are linear combinations of the independent phase-length errors of the two delay lines. Any pair of independent length errors, ϕ_1 and ϕ_2 , can be represented as a linear combination of a common-mode error

$$\gamma = \frac{\phi_1 + \phi_2}{2},$$

and a differential-mode error

$$\delta = \frac{\phi_1 - \phi_2}{2}.$$

In the common error mode, both the phase lengths of both delay lines change equally by the angle γ . In the differential error mode, the phase lengths of the two lines change oppositely by the angle δ . The compressed and reflected pulse amplitudes can be expressed in terms of the two error modes by substituting

$$\phi_1 = \gamma + \delta$$

and

interval, the field amplitude seen at the output is $\frac{1}{\sqrt{2}}$ times the sum of the amplitudes emitted by the delay lines plus the reflection (with coefficient s) from the irises of the klystron wave amplitude. These amplitudes add constructively in the absence of line-length errors. The electric field amplitude of the SLED-II output (compressed) pulse during the N th time interval of duration Δt is

$$\begin{aligned}
E_c = E_{out}^{(N)} &= \frac{1}{\sqrt{2}} [E_{e,1}^{(N)} + E_{e,2}^{(N)}] + sE_0 \\
&= \frac{(1-s^2)e^{-2\tau}}{2} \left[\frac{1 - (se^{-2\tau+j\phi_1})^{N-1}}{1 - se^{-2\tau+j\phi_1}} e^{j\phi_1} \right. \\
&\quad \left. + \frac{1 - (se^{-2\tau+j\phi_2})^{N-1}}{1 - se^{-2\tau+j\phi_2}} e^{j\phi_2} \right] E_0 + sE_0.
\end{aligned} \tag{4}$$

The electric field amplitude reflected back toward the klystron through the hybrid during the N th time interval of duration Δt is

$$\begin{aligned}
E_r^{(N)} &= \frac{1}{\sqrt{2}} [E_{e,1}^{(N)} - E_{e,2}^{(N)}] \\
&= \frac{(1-s^2)e^{-2\tau}}{2} \left[\frac{1 - (se^{-2\tau+j\phi_1})^{N-1}}{1 - se^{-2\tau+j\phi_1}} e^{j\phi_1} \right. \\
&\quad \left. - \frac{1 - (se^{-2\tau+j\phi_2})^{N-1}}{1 - se^{-2\tau+j\phi_2}} e^{j\phi_2} \right] E_0.
\end{aligned} \tag{5}$$

One can define common and differential error modes which are linear combinations of the independent phase-length errors of the two delay lines. Any pair of independent length errors, ϕ_1 and ϕ_2 , can be represented as a linear combination of a common-mode error

$$\gamma = \frac{\phi_1 + \phi_2}{2},$$

and a differential-mode error

$$\delta = \frac{\phi_1 - \phi_2}{2}.$$

In the common error mode, both the phase lengths of both delay lines change equally by the angle γ . In the differential error mode, the phase lengths of the two lines change oppositely by the angle δ . The compressed and reflected pulse amplitudes can be expressed in terms of the two error modes by substituting

$$\phi_1 = \gamma + \delta$$

and

interval, the field amplitude seen at the output is $\frac{1}{\sqrt{2}}$ times the sum of the amplitudes emitted by the delay lines plus the reflection (with coefficient s) from the irises of the klystron wave amplitude. These amplitudes add constructively in the absence of line-length errors. The electric field amplitude of the SLED-II output (compressed) pulse during the N th time interval of duration Δt is

$$\begin{aligned}
E_c = E_{out}^{(N)} &= \frac{1}{\sqrt{2}} [E_{e,1}^{(N)} + E_{e,2}^{(N)}] + sE_0 \\
&= \frac{(1-s^2)e^{-2\tau}}{2} \left[\frac{1 - (se^{-2\tau+j\phi_1})^{N-1}}{1 - se^{-2\tau+j\phi_1}} e^{j\phi_1} \right. \\
&\quad \left. + \frac{1 - (se^{-2\tau+j\phi_2})^{N-1}}{1 - se^{-2\tau+j\phi_2}} e^{j\phi_2} \right] E_0 + sE_0.
\end{aligned} \tag{4}$$

The electric field amplitude reflected back toward the klystron through the hybrid during the N th time interval of duration Δt is

$$\begin{aligned}
E_r^{(N)} &= \frac{1}{\sqrt{2}} [E_{e,1}^{(N)} - E_{e,2}^{(N)}] \\
&= \frac{(1-s^2)e^{-2\tau}}{2} \left[\frac{1 - (se^{-2\tau+j\phi_1})^{N-1}}{1 - se^{-2\tau+j\phi_1}} e^{j\phi_1} \right. \\
&\quad \left. - \frac{1 - (se^{-2\tau+j\phi_2})^{N-1}}{1 - se^{-2\tau+j\phi_2}} e^{j\phi_2} \right] E_0.
\end{aligned} \tag{5}$$

One can define common and differential error modes which are linear combinations of the independent phase-length errors of the two delay lines. Any pair of independent length errors, ϕ_1 and ϕ_2 , can be represented as a linear combination of a common-mode error

$$\gamma = \frac{\phi_1 + \phi_2}{2},$$

and a differential-mode error

$$\delta = \frac{\phi_1 - \phi_2}{2}.$$

In the common error mode, both the phase lengths of both delay lines change equally by the angle γ . In the differential error mode, the phase lengths of the two lines change oppositely by the angle δ . The compressed and reflected pulse amplitudes can be expressed in terms of the two error modes by substituting

$$\phi_1 = \gamma + \delta$$

and

$$\phi_2 = \gamma - \delta$$

into equations (4) and (5).

Common Error Mode:

In the pure common mode ($\phi_1 = \phi_2$, $\delta = 0$), the compressed and reflected pulse amplitudes will be

$$E_c = E_{out}^{(N)} = (1 - s^2) \frac{1 - (se^{-2\tau+j\gamma})^{N-1}}{1 - se^{-2\tau+j\gamma}} e^{-2\tau+j\gamma} E_0 + sE_0$$

and

$$E_r^{(N)} = 0.$$

E_c in general is complex in the presence of delay-line length errors because successive reflections in the delay lines are out of phase. Consequently, the phase of \mathbf{E}_c will be shifted with respect to \mathbf{E}_0 . There will be no reflection \mathbf{E}_r when the lengths of the delay lines are identical and do not break the symmetry of the network, which is designed to direct all power away from the source. Figure 1 shows the SLED-II compressed-pulse power gain and phase shift in response to a common-mode delay-line length error.

Differential Error Mode:

In the pure differential mode ($\phi_1 = -\phi_2$, $\gamma = 0$),

$$E_c = E_{out}^{(N)} = (1 - s^2)e^{-2\tau} \text{Real} \left[\frac{1 - (se^{-2\tau+j\delta})^{N-1}}{1 - se^{-2\tau+j\delta}} e^{j\delta} \right] E_0 + sE_0$$

and

$$E_r^{(N)} = (1 - s^2)e^{-2\tau} \text{Imag} \left[\frac{1 - (se^{-2\tau+j\delta})^{N-1}}{1 - se^{-2\tau+j\delta}} e^{j\delta} \right] E_0.$$

The compressed pulse amplitude E_c is pure real, in phase with the klystron wave amplitude (E_0), so the output wave \mathbf{E}_c is not phase-shifted with respect to the input wave \mathbf{E}_0 . The reflected wave amplitude \mathbf{E}_r is non-zero. Figure 2 shows the SLED-II compressed and reflected power in response to a differential-mode delay-line length error. Figure 3 shows the reflected power response on a log-log scale.

5. An Algorithm for Fine-Tuning the Delay-Line Lengths

The preceding analysis indicates diagnostic signals that can be used for fine-tuning the lengths of the delay lines during operation. A common-mode error is indicated uniquely by an output phase shift. A differential-mode error is indicated by power being reflected back to the klystron. (We assume that other matching errors and their reflections are sufficiently small so that they are not confused with the differential-mode delay-line error.)

A reasonable tuning algorithm might consist of, first, adjusting the delay-line lengths differentially to minimize the power reflected back to the klystron, and, second, adjusting the delay-line lengths in common to minimize the output phase shift. Figure 4 shows a conceptual block diagram of the relationships between the sensors and control actuators.

The output phase shift that uniquely indicates a common-mode delay-line length error can be detected by measuring the phase of the compressed output pulse ($\mathbf{E}_c = \mathbf{E}_{out}^{(N)}$) relative to the low-level rf oscillator during the N th time interval. This measurement is calibrated using the phase of the output pulse relative to the low-level rf oscillator during the *first* time interval ($\mathbf{E}_{out}^{(1)}$). This works because $\mathbf{E}_{out}^{(1)}$ results purely from the reflections off the two SLED-II coupling irises (which we will assume are equal) and contains no component emitted from the delay lines, so the phase of $\mathbf{E}_{out}^{(1)}$ is unaffected by delay-line length errors. Consequently, if the phase of $\mathbf{E}_{out}^{(1)}$ is “zeroed” by adjusting the variable phase shifter, then the phase measurement of \mathbf{E}_c will be calibrated: a non-zero measurement will indicate a common-mode delay-line length error.

Used as a feedforward loop (meaning that corrections are applied to future pulses) with a time constant matched to the thermal expansions of the delay lines, such a tuning algorithm should suffice to maintain the delay-line lengths at their nominal operating set-points. Adjustment of the calibration phase shifter can be performed continuously by a separate feedforward loop. Table 1 summarizes the various sensors and control actuators participating in the system described above.

Quantitative considerations for the tolerances of the sensors are discussed in the next section.

The above tuning algorithm should also be helpful for finding the operating set-points from a random initial state that is within approximately $0.04''$ of differential-mode error, and $0.06''$ of common-mode error, from the nominal operating state. These tolerances are much looser than the tolerances for nominal operation, and apply only to the set of states that can be “captured” and fine-tuned to the nominal operating state.

Initial states that lie outside the above capture tolerances can be adjusted to within the capture tolerances by a human operator. Illustrations of such problematic states are discussed by Farkas in Reference 2.

Table 1. Summary of the sensors and control actuators used to stabilize adjustable shorts

| Sensor | Sample Rate | Time Resol. | Meaning of Signal |
|--------------------------|-------------------|---------------|------------------------------------|
| Reflected power | PRF* | < 0.2 μ s | Nonzero indicates dif.-mode error |
| Output phase in 1st bin | 0.1 Hz | < 0.2 μ s | Nonzero if phase shifter is uncal. |
| Output phase in last bin | PRF* | < 0.2 μ s | Nonzero indicates com.-mode error |
| Compressed power | PRF* | < 0.2 μ s | Max. when errors are eliminated |
| LVDT (linear position) | 0.1 Hz | < 1 s | Readback position of short |
| Actuator | Freq. of Adj'ment | Settle time | Function |
| Phase shifter for calib. | 0.03 Hz | < 10 s | Zeroes detected phase in Bin 1 |
| Stepper motors | 0.03 Hz | < 10 s | Com.- & dif.-mode adjustments |

*"PRF" is the pulse repetition frequency, which nominally is 60 Hz.

6. Precision and Duty Cycle of Tuning Sensors and Actuators

Delay-line length errors remaining after tuning will reduce the peak amplitude of the accelerating field (E_c) and, in the common error mode, they will shift the phase (θ) of the rf wave from its nominal value of 5° off-crest. Assuming a nominal accelerating gradient of $E_c \cos 5^\circ$, we have plotted in Figure 5 the reduction in accelerating gradient,

$$1 - \frac{E_c(\Delta L) \cos(5^\circ + \Delta\theta(\Delta L))}{E_c(0) \cos 5^\circ}, \quad (6)$$

for both the common and differential error modes of a single SLED-II pulse compressor. For differential-mode errors, $\Delta\theta$ is zero and expression (6) reduces to

$$1 - \frac{E_c(\Delta L)}{E_c(0)}. \quad (7)$$

How precisely must one be able to measure rf phase (relative to reference) in order to tune out a common-mode delay-line length error ΔL ? Figure 1 shows that the sensitivity of the output phase shift $\Delta\theta$ to a small common-mode length error ΔL is $\Delta\theta/\Delta L = 1100^\circ/\text{inch}$. If the fractional reduction in accelerating gradient due to common-mode length errors is to be kept less than 0.5%, then Figure 5 indicates that common-mode length errors must be made less than $0.002''$. Consequently, one must be able to move an adjustable shorting

plunger actuator by 0.002" and to measure relative rf phase with an accuracy of at least $1100^\circ/\text{inch} \times 0.002\text{ inch} = 2.2^\circ$ near 0° in order to adequately tune out a common-mode delay-line length error. If thermal stabilization is used for length adjustment, instead of adjustable shorting plungers, then equation (1) implies that the temperature stability equivalent to the 0.002" length stability is 0.077°C .

How precisely must one be able to measure reflected rf power in order to tune out a differential-mode length error ΔL ? If the fractional reduction in accelerating gradient due to differential-mode length errors is to be kept less than 0.5%, then Figure 5 indicates that differential-mode length errors must be made less than 0.004". Consequently, one must be able to move an adjustable shorting plunger actuator by 0.004" (which is a looser tolerance than that imposed by the common-mode case) and to measure reflected power relative to klystron power (Figure 3) with a relative precision of 2% (1 MW reflected back to a 50-MW klystron) in order to adequately tune out a differential-mode delay-line length error.

How often must the delay line lengths be re-adjusted? Assuming the rate of temperature change inside End Station B is less than $1^\circ\text{C}/\text{h}$ (consistent with preliminary measurements by R. Fuller) the delay line lengths must be re-adjusted at least every 280 seconds in order to achieve the 0.077°C temperature stability necessary for 0.5% gradient stability.

Following the above examples, which were for 0.5% gradient stability, Table 2 indicates the minimum precision and duty cycle of the sensors and actuators that is necessary to achieve several different levels of gradient stability. The sensor and actuator precisions quoted in Table 2 have been chosen such that the desired gradient stability will be exceeded in one step; actual tolerances on the sensors and actuators would have to be *several times tighter* than the values in Table 2 for a computerized control algorithm to be able to bracket the desired operating point.

Table 2. Minimum precision and duty cycle of sensors and actuators necessary to achieve different levels of accelerating-gradient stability

| Accelerating-gradient stability | 0.1% | 0.2% | 0.5% | 1% |
|---|----------------|----------------|----------------|---------------|
| Linear actuator step size | 0.0006" | 0.001" | 0.002" | 0.004" |
| Equivalent temperature stability ($^\circ\text{C}$) | 0.023 $^\circ$ | 0.038 $^\circ$ | 0.077 $^\circ$ | 0.15 $^\circ$ |
| Phase resolution near 0° | 0.66 $^\circ$ | 1.1 $^\circ$ | 2.2 $^\circ$ | 4.4 $^\circ$ |
| Resol. of reflected power rel. to klystron power | 0.5% | 0.9% | 2% | 5% |
| Time between corrections* | 83 s | 140 s | 280 s | 540 s |

*Assuming temperature change of $1^\circ\text{C}/\text{h}$.

For example, to achieve the 0.1% level of accelerating-gradient stability, one should strive for approximately 0.0002" step-size, 0.2° phase-detection resolution, 0.2% reflected power resolution (relative to klystron power), and 30 seconds between corrections. Phase and

amplitude detectors in use at the SLC already provide approximately 0.1° phase resolution, 0.1% power resolution, and 30-ns time resolution (15-MHz bandwidth) for a single sample per rf pulse, indicating that it should be possible to achieve the tolerances necessary for 0.1% gradient stability from SLED-II at the NLCTA by using feedforward correction of the adjustable shorts, even without precise temperature regulation of the 120-foot-long delay lines. We should plan to do this well.

Other limitations besides SLED-II delay-line length stability may arise when trying to achieve accelerating-gradient stability better than a percent. Phase ripple in the klystron pulse caused, for example, by voltage ripple in the modulator pulse, may limit the ability to precisely tune the delay-line lengths. Some type of klystron phase-stabilization feedforward control may be needed to monitor the phase of the klystron output pulse in intervals of several nanoseconds each and modify the phase of the low-level rf drive waveform in corresponding intervals so as to correct the klystron output phase on future pulses.

REFERENCES

1. P. B. Wilson, Z. D. Farkas, and R. D. Ruth, "SLED II: A New Method of RF Pulse Compression" (SLAC-PUB-5782), 1990 Linear Accelerator Conference, Albuquerque, New Mexico, September 10-14, 1990 (pp. 204-206 in proceedings).
2. Z. D. Farkas, "Tuning SLED-II" (SLAC-AAS-Note 79), July 1993.

FIGURE CAPTIONS

- 1) SLED-II compressed-pulse power gain and phase shift in response to a common-mode delay-line length error.
- 2) SLED-II compressed and reflected power in response to a differential-mode delay-line length error.
- 3) Log-log plot of the reflected power in response to a differential-mode delay-line length error.
- 4) Conceptual block diagram of the delay-line length tuning components.
- 5) Delay-line length error tolerances.

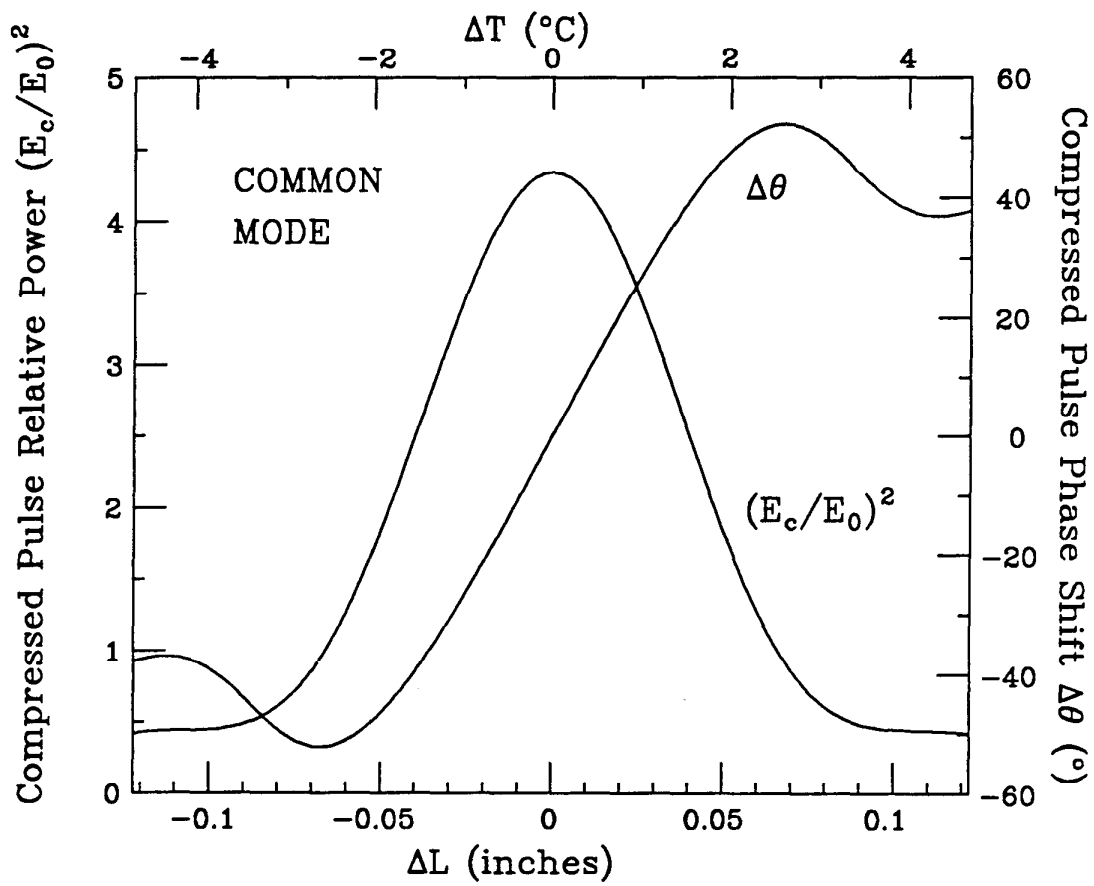


Figure 1.