NLCTA-Note #43

March 8, 1995

**Subject:** Klystron Phase Variation due to Fluctuations in Beam Voltage

**Authors:** E. Wright, R. Miller

## 1. Introduction

This note derives the formulas used to evaluate klystron phase variation due to changes in beam voltage. We will estimate the intra-pulse phase variation based on the minimum beam voltage ripple thought to be obtainable from a properly tuned NLCTA modulator. Measured data from XL-1 using a modulator similar to that for NLCTA is also included.

## 2. Background

The change in phase across a klystron amplifier as a function of beam voltage is primarily due to the change in transit-time of the electrons from the input gap to the output gap. The phase length of a klystron can be described as follows,

$$\varphi_{i,o} = \frac{kL_{i,o}}{\beta} \tag{1}$$

where $L_{i,o}$ is the distance from the input cavity to the output cavity, $k$ is the free space wave number, and $\beta$ is the electron velocity normalized to the speed of light in free space. To evaluate the phase change as a function of beam voltage, the following expansion is used.

$$\frac{\partial\varphi}{\partial V} = \frac{\partial\varphi}{\partial\beta}\frac{\partial\beta}{\partial\gamma}\frac{\partial\gamma}{\partial V} \tag{2}$$

Differentiating equation (1), we obtain the first term in the expression.

$$\frac{\partial\varphi_{i,o}}{\partial\beta} = \frac{-kL_{i,o}}{\beta^2} \tag{3}$$

The second and third terms are obtained in similar fashion by differentiating as follows.

$$\beta = \sqrt{1-\frac{1}{\gamma^2}} \Rightarrow \frac{\partial\beta}{\partial\gamma} = \frac{1}{\beta\gamma^3} \tag{4}$$

$$\gamma = 1 + \frac{eV}{mc^2} \Rightarrow \frac{\partial \gamma}{\partial V} = \frac{e}{mc^2} \tag{5}$$

Combining (3), (4), (5), we obtain the following expression.

$$\frac{\partial \varphi_{i,o}}{\partial V} = \frac{-ekL_{i,o}}{mc^2 \beta^3 \gamma^3} = \frac{-ekL_{i,o}}{mc^2 \left(\sqrt{\gamma^2 - 1}\right)^3} \left(\tfrac{rad}{V}\right) \tag{6}$$

$$\frac{\partial \varphi_{i,o}}{\partial V} = \frac{-360 eL_{i,o}}{mc^2 \lambda_o \left(\sqrt{\gamma^2 - 1}\right)^3} \left(\tfrac{\deg}{V}\right) \tag{7}$$

$$\frac{\partial V}{V} = \frac{-mc^2 \lambda_o \left(\sqrt{\gamma^2 - 1}\right)^3}{360 eL_{i,o} V} \partial \varphi_{i,o} \tag{8}$$

More useful forms of equation (6) can be obtained by a simple rearrangement of terms, as follows.

**3. Evaluation for the XL-Series Klystron.**

A list of parameters for the XL-Series klystron can be seen in table 1. The two parameters of interest for evaluation of (7) and (8) are beam voltage and circuit length. The electron beam does not gain the full 440 keV of energy due to space charge depression of the beam. With potential depression, the electrons have an average of 425.5 keV of useful energy, and this voltage should be used in the expression. Evaluating (7) we get the following:

$$\frac{\partial \varphi_{i,o}}{\partial V} = \frac{-360 \cdot 307.9}{511{,}000 \cdot 26.24 \cdot 3.634} = -0.00227 \left(\tfrac{\deg}{V}\right) \tag{9}$$

So with a cathode voltage of 440 kV, we can expect to see 2.3 degrees of phase change across the klystron for every kilovolt change in beam voltage. A typical line-type modulator can be tuned such that the voltage ripple is on the order of 1%, or approximately 10 degrees rf phase variation during the pulse.

| **Parameter** | **Value** | **Units** |
|---|---|---|
| Beam Voltage | 440 | kV |

| | | |
|---|---|---|
| Beam Current | 350 | A |
| Microperveance | 1.2 | $A/V^{3/2}$ |
| Frequency | 11.424 | GHz |
| Peak RF Output Power | 50 | MW |
| Average Power | 13.5 | kW |
| Gain | >50 | dB |
| RF Pulse Width | 1.5 | ms |
| PRF | 180 | pps |
| Tunnel Diameter | 9.525 | mm |
| Beam Diameter | 6.35 | mm |
| Circuit Length (i/o) | 307.9 | mm |
| Cathode Diameter | 71.4 | mm |
| Beam Area Convergence | 125:1 | |
| Cathode Loading | 12.8 | $A/cm^2$ (max.) |
| Magnetic Field | 0.47 | T |
| Magnet Power | 25. | kW |

**TABLE 1**: XL-Series klystron design parameters

**4. Measured Data.**

Figures 1 and 2 show measured data for the XL1 klystron. In figure 1, the cathode voltage varies from -436 kV to -440.5 kV during the rf pulse. The change in phase across the klystron due to this voltage variation is approximately 10 degrees, as predicted by the above equations.

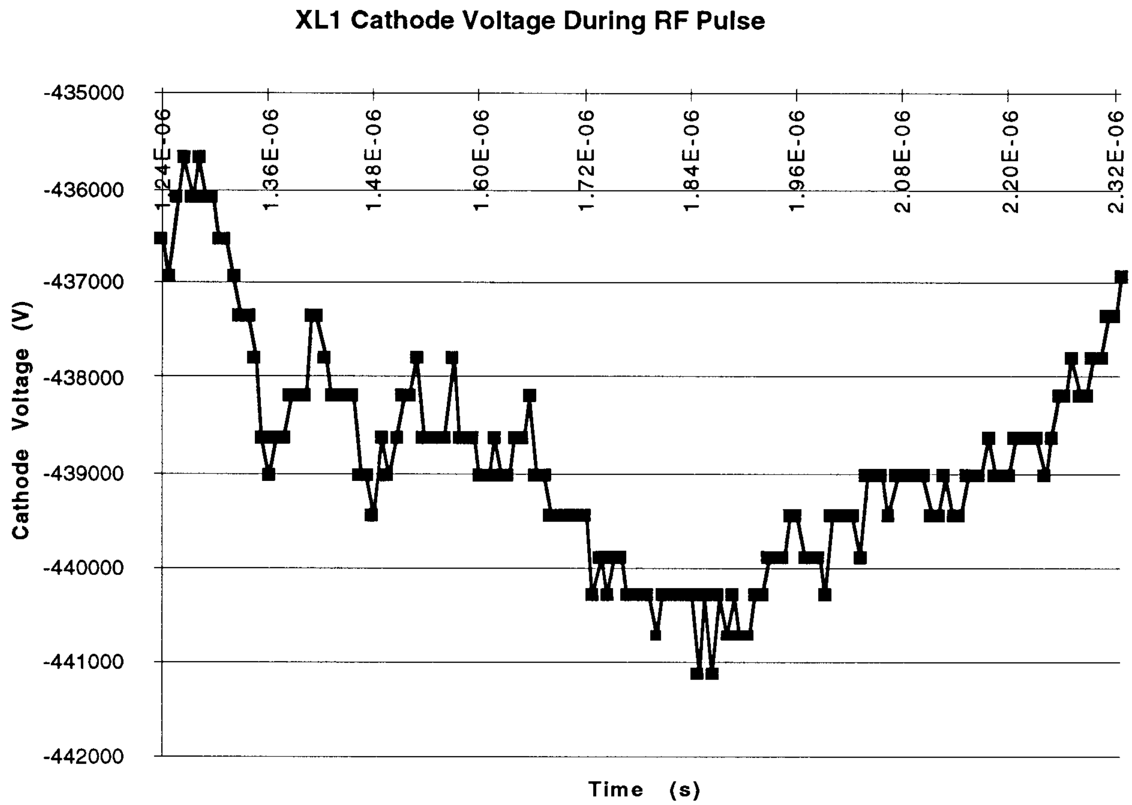


**Figure 1:** Klystron Cathode Voltage Variation During the 1.05 μs rf Pulse.

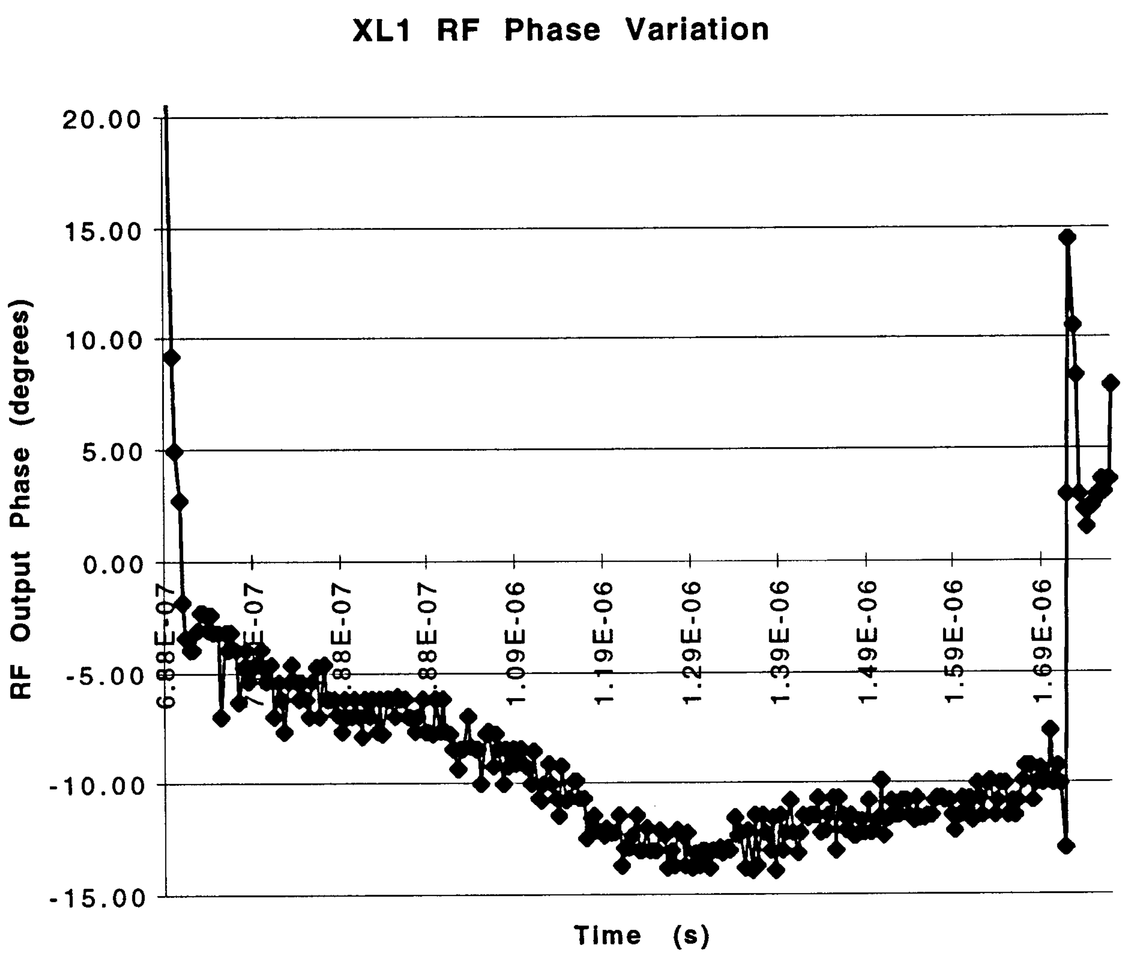


**Figure 2:** Klystron RF Output Phase Variation for 1.05 μs rf Pulse.