TABLE III. Summary of experimental results—36°-rotated *Y*-cut samples. $U = 7.33$ km/s, $\rho_0 = 4.64$ Mg/m^3, and $\alpha = 1.00$. Notation is the same as that used in Table I.

Shot No.	u_0 (m/s)	u (m/s)	T (GPa)	u/U ($\times 10^{-4}$)	$-\eta$ ($\times 10^{-4}$)	$i_i l/AU$ (mC/m^2)	i_f/i_i	P_3^η (mC/m^2)	k[a]
P-1107	68.01	6.35	0.216	8.66	8.66	3.96	1.50	3.97	18.35
P-1106	108.0	10.32	0.351	14.1	14.07	6.59	1.94	6.50	18.77
Q-1091	36.48	11.24	0.382	15.33	15.32	7.166	1.45	7.177	18.75
Q-1095	58.84	18.12	0.616	24.72	24.69	11.43	1.50	11.46	18.57
Q-1092	61.63	18.98	0.646	25.90	25.87	12.09	1.42	12.12	18.72
Q-1093	71.30	21.96	0.747	29.96	29.92	13.94	1.48	13.98	18.66

[a] The fit to the *k*-vs-stress data is $k = 18.64$ in C/m^2 GPa, standard deviation = 0.16.

lithium niobate. The scatter in the *Y*-cut data is probably the result of the combined effect of tilt, which prevents a reading at $t = t_0$ and the large electromechanical coupling effect affecting the observed value of the initial current. There is no discernible nonlinear effect in the data for the 36°-rotated—*Y*-cut samples.

The shock velocity determined from either the current pulse duration measurements or from the quartz gauge impact and propagated wave profile measurements are shown in Table IV. Given the experimental accuracy of ±1 and $\pm\frac{1}{2}\%$, respectively, for the two techniques and the small strains of the experiment, no change in wave speed with strain was detected. The data of Table IV generally indicate ranges which are within the experimental accuracies. There is good agreement between the two independent techniques used to measure the shock velocity of the *Z*-cut samples.

VI. DISCUSSION OF RESULTS

Material constants and effects observed in the present investigation which are to be discussed and compared to prior work include second- and third-order piezoelectric stress constants, second-order elastic constants as determined from the shock velocity, electromechanical coupling effects on the current pulse, and thresholds for shock-induced conductivity.

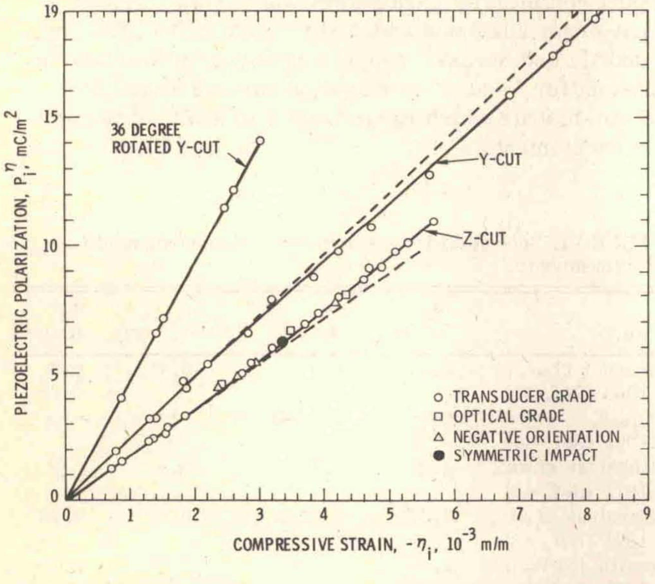

FIG. 5. Piezoelectric polarization versus strain for the three crystallographic orientations of lithium niobate investiaged in the present investigation. The unusually low strains achieved in the present investigation compared to conventional impact-loading experiments are of particular interest. The dashed lines are extrapolations of the linear behavior observed at small strains.

A. Piezoelectric stress constants

The second- and third-order piezoelectric constants derived from least-squares polynomial fits to the piezoelectric polarization versus strain data are summarized in Table V and compared to prior work on quartz with the same technique. The experimental error in the determination of the e_{33} constant is about 2%. There is a possible error of 3% in the analysis of the *Y*- and rotated-cut data because of the interpretation based on uniaxial strain.

In spite of the large number of samples, crystal boules and grades, the precision indicated by the standard error of from 0.9 to 1.5% can be fully accounted for by the precision of the measurement technique. This observation indicates that the material constants are reproducible from sample to sample to a degree which is small compared to the standard errors. Another indication of the reproducibility of the material constants comes from the observation that the present piezoelectric constants differ only slightly from earlier reports of this same investigation when less complete data were available.[4,15,25]

The present observation of the reproducibility of material constants is in agreement with similar conclusions drawn from measurements of the linear and nonlinear hydrostatic piezoelectric constants[16] and data in the Appendix. It appears that the present techniques for crystal growth, poling, and quality control to select

TABLE IV. Shock velocity measurements.

Experiment[a]	U (km/s)	Standard deviation (km/s)	Range (km/s)	No. observations
Z-cut A	7.33	0.038	−0.05 +0.07	26
Z-cut B	7.32	0.030	±0.03	3
Y-cut A	6.90	0.038	±0.06	10
Rotated cut A	7.35	0.057	±0.07	6

[a] "A" series of experiments determined shock velocity from sample thickness and current pulse duration. "B" series experiments determined shock velocity from sample thickness and quartz gauge measurements of the time difference between impact and wave arrival at rear surface.

TABLE V. Second- and third-order piezoelectric stress constants of lithium niobate and quartz. It is conventional to assign a positive sign to the longitudinal second-order piezoelectric constants and in this tabulation we have followed that practice. Since strains are normally considered positive in tension, the signs of the third-order constants are assigned on that basis.

Sample Lithium niobate	e_{ij} (C/m^2)	e_{ijk} (C/m^2)	e_{ijk}/e_{ij} (C/m^2)
$i=j=k=3$	1.80 ± 0.016	-21 ± 7	-11
$i=j=k=2$	2.37 ± 0.036	21 ± 10	$+9$
$i=1,\ j=5$	3.83[a]	···	···
Rotated cut	4.65 ± 0.053	0	···
Quartz			
$i=j=k=1$	0.171 ± 0.0009	-2.62 ± 0.05	-15.3

[a] A value of the e_{15} constant is derived from the fit to the rotated-cut data by solution of Eq. (2). The e_{22} and e_{15} constants determined from the present investigation were used in the calculation with the e_{31} constant determined by Smith and Welsh (Ref. 39). Since the e_{31} constant is relatively small, the calculated e_{15} constant is not sensitive to the value chosen for e_{31}.

transducer-grade lithium niobate yields samples with material constants which are reproducible to a precision of substantially less than 1%.

Although the conclusion on the reproducibility of material constants is drawn from observations of the second-order piezoelectric constants, it should be observed that the reproducibility extends to the elastic constants as well. The current measurement from which the piezoelectric constants are derived is directly dependent on the elastic constants through the dependence of the current on shock velocity. Sample-to-sample variations in the shock velocity would cause corresponding variations in the current and affect the precision of the measurements.

The present value of e_{33} is sufficiently accurate to justify making a correction for the change in polarization caused by adiabatic heating and the pyroelectric effect. For the relatively small compressions of the present experiments, the compression is adiabatic and the increase in temperature ΔT is

$$\Delta T = [(V_0/V)^{\Gamma} - 1]T_0, \tag{8}$$

where T_0 is the initial temperature, V_0 is the initial volume, V is the compressed volume, and Γ is the Grüneisen coefficient. For small compressions $\Delta T = \Gamma S T_0$, where $S = 1 - (V_0/V)$, and the resulting pyroelectric polarization per unit strain is $(\partial P^S/\partial S^T) = \Gamma T_0 \tau$, where P^S is the spontaneous polarization and τ is the *primary* pyroelectric constant. In the present experiments $\Gamma = 1.38$ and $\tau = 5.0 \times 10^{-5}$ C/m^2 K, and it is found that $(\partial P^S/\partial S^T) = 2.07 \times 10^{-2}$ C/m^2 which is 1.2% of e_{33}.[38] The e_{33} reported in Table V has been corrected for the pyroelectric contribution. From symmetry considerations it is known that there is no effect on e_{22} and the effect is negligible for the rotated cut.

The e_{22} and e_{15} values reported by the various investigators and summarized in Table VI show a standard deviation of about 2%, whereas the e_{33} values (as well as those for d_{33}, which is not tabulated) show a standard deviation of 12%. This poor reproducibility of values for e_{33} is probably a result of material reproducibility problems in crystals utilized in earlier investigations. The present investigation included examination of material reproducibility in some detail and provides a direct measure of e_{33} with well-defined errors, and the present value of e_{33} is significantly greater than reported in prior work. Recent measurements of the hydrostatic piezoelectric constant,[16] which is the sum of d_{33} and $2d_{31}$, indicated that d_{33} is also significantly greater than that reported in prior work.

The third-order piezoelectric stress constants determined in the present investigation are shown in Table V and compared to previous measurements on X-cut quartz. The errors of the present third-order constants are large since higher-order piezoelectric contributions are small relative to the second-order contribution. Nevertheless, the third-order contributions are readily apparent and well defined, and the errors of the present work are less than has been achieved with other techniques. The higher-order constant of the Y-cut material is particularly interesting since the sign is positive compared to the negative sign observed on Z-cut lithium niobate and X-cut quartz.

The only direct comparison of the present measurements to other work comes from the work of Korobov and Lyamov[8] who gave order-of-magnitude estimates for various third-order constants of lithium niobate. Their estimate of 10 C/m^2 for e_{333} is about a factor of 2 smaller than the present value. For other third-order constants in lithium niobate, Korobov and Lyamov[8] give order-of-magnitude estimates for the various constants which range from -3 to 190 C/m^2. From static electric field dependencies of acoustic resonances in lithium niobate, Thompson and Quate[2] report nonlinearity parameters which yield various third-order constants which vary from 12 to 150 C/m^2. Luukkala and Suraka[11] report a nonlinear piezoelectric constant for Y-cut Z-propagating surface waves in lithium niobate which range from 8 to 22 C/m^2 in various experiments.

TABLE VI. Second-order piezoelectric stress constants of lithium niobate.

Author	e_{22} (C/m^2)	e_{33} (C/m^2)	e_{15} (C/m^2)	e_{31} (C/m^2)
Warner *et al.*, 1966 (Ref. 40)	2.5	1.3	3.7	0.2
Smith, 1971 (Ref. 41)	···	1.62–1.78	···	···
Chkalova *et al.*, 1971 (Ref. 42)	2.5	1.7	3.8	···
Korolyuk *et al.*, 1971 (Ref. 43)	2.52	1.67 (1.72)	3.60	0.75
Smith and Welsh 1971 (Ref. 39)	2.43	1.33	3.76	0.23
Graham, 1973 (Ref. 15)	···	1.78[a]	···	···
Nakagawa *et al.*, 1973 (Ref. 24)	2.5	1.42	3.8	0.35
Present work	2.37	1.80[a]	3.83	···

[a] Corrected for a pyroelectric contribution of 1.2%.