The sample and electrical configuration is shown in Fig. 3. One-dimensional electrical conditions within the active volume of the sample are achieved by a guard-ring configuration which restricts the region of observation to the central portion of the disk. Due to the symmetry of the strain-induced polarization and the electric fields, the active charge-collecting area extends to a diameter located at the center of the insulating ring. The resistive loads were varied in the range from about 3 to 15 Ω from experiment to experiment to keep the output voltage approximately equal to the 6.54-V calibration pulse.[33] Most of the samples were oriented such that the shock propagated from the grounded negative-polarity electrode to the positive-polarity electrode.

Experiments from which data on piezoelectric constants were obtained were conducted on 27 *Z*-cut samples, 15 *Y*-cut samples, and 6 36°-rotated—*Y*-cut samples. Data on *Z*-cut samples were obtained from samples cut from 9 different single-crystal boules. Other experiments whose detailed results are to be reported elsewhere were conducted to study the shock-induced conductivity which is, in many respects, similar to that observed in *X*-cut quartz.[36,37]

Experiments were also conducted to determine the Hugoniot elastic limit and wave speed in the *Z*-cut samples. These experiments were conducted with the quartz gauge "front-back" configuration[33] in which the impact load is applied and measured by an impacting quartz gauge. The propagated wave profile is also monitored by a quartz gauge, which provides an accurate time-resolved measure of the wave profile from which the Hugoniot elastic limit can be determined. Front-back configuration experiments were also conducted below the elastic limit to determine the shock velocity to an accuracy of ± $\frac{1}{2}$%. Wave transit time measurements obtained from the durations of the current pulses give velocity to an accuracy of ±1%.

Most of the material was a selected "transducer grade"; however, three optical-grade *Z*-cut samples were also investigated. The optical-grade material has very low residual strain and fewer light-scattering centers but is only available in diameters up to 12.5 mm. Our transducer-grade material was selected by optical inspection to avoid samples with large internal strains. The crystals were free of cracks of bubbles when viewed by a high-intensity lamp; inclusions were less than 1/cm^3. The crystals were clean, pale yellow, single domain, and twin free.

The samples were right-circular-cylindrical disks of various diameters and thicknesses. Early in the investigation diameters of the *Z*-cut samples were typically 19 mm and thicknesses were 2.5 mm. Specimens of optical-grade material were typically 12.5 mm in diameter and 2.5 mm in thickness. The first *Y*-cut samples were 25 mm in diameter and 2.5 mm thick. Later in the investigation larger crystals became available and *Z*- and *Y*-cut samples 33 mm in diameter and 6.3 mm in thickness were used. All the 36°-rotated—*Y*-cut samples were of this larger size. In general, the large-diameter samples contained larger residual strains. All samples were grown and poled by Crystal Technology, Inc., and the disks were x-ray oriented within 1° and fabricated by either Crystal Technology, Inc. or Specialty Engineering Associates.

V. RESULTS

A typical current pulse obtained from an experiment on a *Z*-cut sample (Fig. 4) is characterized by a jump in current while the stress is being applied over the entire active area followed by a slow increase in current with time. The magnitudes of the increases in current with time are similar for *Z*-cut lithium niobate and *X*-cut quartz,[14] but solutions for the current from Eqs. (3) and (6) show that, while the increase in current for quartz is dominated by the effect of the strain u/U, the increase in current for lithium niobate is dominated by the electromechanical coupling effects. A value of $\alpha = 1.00$ was used in Eq. (4) to compute the piezoelectric polarization from the initial current jump since, within the reproducibility of the data, there was no discernible change in the magnitude of the increase in current with time as the input strain was changed.

The increase in current during the shock-wave transit time for the *Y*- and 36°-rotated—*Y*-cut samples amounted to about 50% of the initial value for the quartz impactor experiments due to the electromechanical coupling effect.

The theory used to interpret the current pulses presumes that the sample is elastic and that the conductivity is zero. Hugoniot elastic limit measurements for the *Z*-cut samples indicated a peak stress of 2.5 GPa which relaxed in time to a stress of 1.9 GPa. Relatively low shock-induced conductivity thresholds significantly limited the maximum strains which could be used in the experiments.

Detailed tabulation of the experimental results for *Z*-cut lithium niobate is given in Table I. It is notable that the strains and particle velocities in the present investigation are, by far, the lowest achieved in shock-loading experiments in which active measurements are taken. The lowest strain of 7×10^{-4} overlaps the maximum strains obtained in the static high-pressure ultrasonic measurements and those achieved in surface acoustic waves at microwave frequencies.

In the tabulation it is relatively easy to note the extent of the electromechanical coupling from the tabulated values of i_f/i_i. The larger values obtained when using the PMMA impactors (prefix P on Shot No.) are as expected from solutions of Eq. (6).

In a number of cases a slight conductivity effect is noted, but the effect is not sufficient to cause an error in computation of the piezoelectric polarization from the observed initial current.

Results of the experiments on *Y*- and 36°-rotated—*Y*-cut samples are shown in Tables II and III, respectively.

A more detailed plot of the results from individual experiments is shown for the three orientations in Fig. 5. The data on *Z*-cut lithium niobate were obtained under a wide range of conditions which are indicated in the symbols. It is apparent that the responses of the

TABLE I. Summary of experimental results—Z-cut samples. u_0 is the impact velocity, u is the particle velocity, T is the longitudinal component of stress, η is the material strain, i_i is the initial current jump, i_f is the current at wave transit time, l is the specimen thickness, A is the charge-collecting area computed from a diameter to the center of the insulating ring, U is the shock velocity, P_i^η is the piezoelectric polarization computed from Eq. (3), and k is the piezoelectric current coefficient computed from $k=i_i l/TAU$. $U=7.33$ km/s, $\rho_0=4.64$ Mg/m^3, and $\alpha=1.00$.

Shot No. [a]	u_0 (m/s)	u (m/s)	T (GPa)	$S=u/U$ ($\times10^{-4}$)	$-\eta$ [b] ($\times10^{-4}$)	$i_i l/AU$ (mC/m^2)	i_f/i_i	P_3^η (mC/m^2)	k [c] (mC/m^2 GPa)	Remarks
P-1101	56.28	5.234	0.178	7.14	7.14	1.31	1.08	1.31	7.35	
Q-868	20.79	6.40	0.218	8.74	8.73	1.56	• • •	1.56	7.16	
P-1105	100.5	9.56	0.325	13.0	13.0	2.40	1.11	2.40	7.38	
Q-1100	32.23	9.93	0.338	13.54	13.53	2.46	• • •	2.46	7.27	Nonlinear current ramp
Q-853	35.71	11.00	0.374	15.01	15.00	2.66	• • •	2.66	7.11	
Q-1102	37.42	11.52	0.392	15.72	15.71	2.90	1.07	2.90	7.40	
Q-857	43.56	13.41	0.456	18.30	18.28	3.31	1.06	3.32	7.26	
Q-1010-N	55.86	17.20	0.585	23.47	23.44	4.39	1.05	4.40	7.50	Negative polarity
Q-1024-O	57.27	17.64	0.600	24.07	24.04	4.50	1.07	4.51	7.50	Optical grade
Q-1009-N	63.00	19.40	0.660	26.47	26.43	4.86	• • •	4.88	7.36	Negative polarity
Q-883	64.76	19.95	0.678	27.21	27.17	4.98	• • •	4.99	7.35	
Q-1017	67.84	20.90	0.711	28.51	28.47	5.33	1.06	5.34	7.50	
Q-1015-N	68.79	21.19	0.721	28.91	28.87	5.31	1.06	5.33	7.36	Negative polarity
Q-848	75.70	23.31	0.793	31.81	31.76	5.98	• • •	6.00	7.54	
L-1119	49.07	24.54	0.835	33.47	33.41	6.16	• • •	6.18		Symmetric impact, slight conductivity
Q-1032-O	83.59	25.74	0.875	35.12	35.06	6.58	1.07	6.60	7.52	
Q-858	88.04	27.12	0.922	36.99	36.92	6.89	1.07	6.92	7.47	
Q-914	93.00	28.64	0.974	39.07	38.99	7.23	1.06	7.26	7.42	
Q-1062	100.4	30.91	1.051	42.17	42.08	7.87	• • •	7.90	7.49	Slight conductivity
Q-1016-N	100.9	31.07	1.057	42.38	42.29	7.78	• • •	7.82	7.36	Negative polarity, slight conductivity
Q-1023-O	102.0	31.42	1.068	42.87	42.78	7.93	1.08	7.96	7.43	Optical grade
Q-851	109.6	33.76	1.148	46.05	45.94	8.50	• • •	8.54	7.40	Slight conductivity
Q-881	112.1	34.52	1.174	47.09	46.98	8.81	1.08	8.86	7.50	
Q-937	116.8	35.98	1.224	49.08	48.96	9.02	1.10	9.06	7.37	
Q-939	121.7	37.49	1.275	51.15	51.02	9.50	• • •	9.55	7.45	Slight conductivity
Q-938	126.1	38.84	1.321	52.98	52.84	9.86	• • •	9.91	7.46	Slight conductivity
Q-909	136.8	42.13	1.433	57.48	57.31	10.85	• • •	10.91	7.57	Slight conductivity

[a] The prefix on the Shot No. indicates Q for an X-cut quartz impactor, L for a Z-cut lithium niobate impactor, and P for a PMMA impactor. The suffix O indicates an optical-grade sample and the suffix N indicates a negative-polarity orientation in which the shock front propagates from the positive to the negative electrode. Shot numbers are chronological and numbers greater than 1060 indicate experiments on 32-mm-diam samples.

[b] $\eta = S(\frac{1}{2}S-1)$. See Ref. 14.

[c] The fit to the k-vs-stress data is $k=[7.26 \pm 0.044 + (0.18 \pm 0.05)T]$ mC/m^2 GPa, standard deviation $= 0.092$.

optical-grade and transducer-grade materials were the same. The data also indicate that there is no difference in the response of negative orientation samples for which the shock propagation direction is reversed relative to the direction of the spontaneous polarization.

The Y-cut data in Fig. 5 show that the nonlinear constant is of opposite sign to that observed for Z-cut

TABLE II. Summary of experimental results—Y-cut samples. $U=6.88$ 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. [a]	u_0 (m/s)	u (m/s)	T (GPa)	$S=u/U$ ($\times10^{-4}$)	$-\eta$ ($\times10^{-4}$)	$i_i l/AU$ (mC/m^2	i_f/i_i	P_2^η (mC/m^2)	k [b]
P-1103	56.73	5.482	0.175	7.969	7.937	1.83	1.77	1.83	10.47
Q-1087	27.87	8.974	0.286	13.04	13.03	3.11	1.53	3.11	10.87
P-1104	96.37	9.67	0.309	14.06	14.05	3.19	1.65	3.20	10.33
Q-1064	39.13	12.60	0.402	18.31	18.29	4.63	• • •	4.64	11.52
Q-1088	39.80	12.81	0.409	18.62	18.60	4.39	1.53	4.40	10.73
Q-1056	47.24	15.21	0.486	22.11	22.09	5.27	• • •	5.28	10.84
Q-1089	60.56	19.50	0.622	28.32	28.30	6.56	1.57	6.58	10.54
Q-1067	67.94	21.88	0.698	31.80	31.75	7.69	1.49	7.71	11.02
Q-1055	82.37	26.52	0.847	38.55	38.48	8.72	• • •	8.78	10.30
Q-1054	90.04	28.99	0.925	42.14	42.05	9.70	1.46	9.73	10.48
Q-1098	100.1	32.24	1.029	46.86	46.75	10.65	1.53	10.70	10.35
Q-1053	120.2	38.70	1.235	56.26	56.10	12.75	1.45	12.82	10.32
Q-1094	146.4	47.12	1.504	68.50	68.27	15.64	1.53	15.75	10.40
Q-1066	161.1	51.87	1.66	75.40	75.12	17.24	1.52	17.37	10.39
Q-1096	166.1	53.47	1.71	77.72	77.42	17.69	1.50	17.83	10.35
Q-1099	175.7	56.54	. . .	82.19	81.85	18.43	. . .	18.58	10.24

[a] Shot numbers greater than 1085 indicate experiments on 32-mm-diam samples.

[b] The fit to the k-vs-stress data is $k=[10.9 \pm 0.14 - (0.34 \pm 0.14)T]$ mC/m^2 GPa, standard deviation $= 0.30$.