measured particle velocity to various specimens of X-cut quartz disks and to record the current produced at stress levels from 3 kbar to about 50 kbar. Analysis of the current produced by the constant stress input permits the determination of certain of the physical properties of shock-loaded quartz, shows the effect of deviations from one-dimensional conditions, and serves as a quantitative calibration of the quartz disk for use as a gauge.

For a well-defined impact experiment, the angular misalignment of the impacting surface of the projectile facing and the impacted surface of the specimen disk (we call this "tilt") is sufficiently small so that the entire electrode of the disk is impacted in a time which is short compared to the stress wave transit time (typically 440 nsec). In the early experiments a propellant gun[10] with a $1\frac{5}{8}$-in. bore was used to accelerate the projectile to various velocities. A $2\frac{1}{2}$-in.-bore compressed-gas gun[11] has been used for the experiments performed most recently. Mean tilt values obtained were 5×10^{-4} rad for the gas gun and 1×10^{-3} rad for the propellant gun. The velocity of the projectile at impact is obtained by measuring the time interval for the projectile to move between two or sometimes three pairs of velocity stations in the immediate vicinity of the impact plane. The impact velocity thus obtained is known to $\pm0.5\%$.[12]

An important characteristic of the experiment is that the tilt of the impacting surfaces is indicated directly from the risetime of the current waveform. Furthermore, if partial loss of vacuum in the region ahead of the projectily occurs before impact, the resulting pressure build-up is clearly indicated by a slight precursor to the rapid rise in current due to the physical impact of the disks.

Nanosecond-type pulse circuitry was employed for all electrical measurements. The majority of the experiments were performed with signals imposed directly on the deflection plates of a Tektronix 517 oscilloscope. The resulting transmission line and oscilloscope risetime was measured to be 3 nsec. Some of the experiments were performed with Tektronix 545 oscilloscopes and Type L preamplifiers which gave a risetime of 12 nsec. The type of instrumentation used for a particular experiment is indicated in the tabulated results.

The characteristics of the experimental technique are such that the resulting data are remarkably self-contained, and the stress input conditions imposed on the specimen well-defined. All mechanical and electrical properties influence the data directly and the effect of qualifying conditions, such as tilt and pressure build-up, are clearly indicated on the records. This leads to a high degree of confidence in the physical circumstances under which the data were obtained. The experimental error in relating the values of particle velocity and current is estimated to be $\pm2\frac{1}{2}\%$.

THE GUARD-RING CONFIGURATION

A fully electroded disk with a small diameter-to-thickness ratio (d/l) shows considerable distortion to the idealized current pulse as is clearly shown in the typical $d/l=2$ record in Fig. 3. The current increases about 70% from the initial jump at $t=0$ to the final value at wave transit time, and the initial current is depressed about 15% below the one-dimensional case. Disks of various d/l ratios may be used for gauges on certain experiments, as will be shown later; but to study intrinsic physical properties and obtain undistorted gauge records, a one-dimensional configuration must be used. One-dimensional electric field and one-dimensional mechanical strain conditions are selectively obtained by using a quartz disk with a guard ring configuration. The inner portion of the disk is isolated electrically from the outer portion by separating the vapor-coated electrode into two regions as shown in Fig. 4. The potential on the two electrodes is kept approximately the same[13] by using resistive electrical loads whose resistances are in inverse proportion to the areas of the electrodes. By the proper choice of dimensions, the current observed from the inner region is obtained under one-dimensional conditions for the full transit time in the disk.

The electric field due to the piezoelectric effect in the stressed and unstressed portions of the disk is distorted by a number of mechanisms. At the outer edge of the disk the discontinuity in electric potential and dielectric permittivity causes electric field fringing in a manner similar to that encountered for parallel-plate capacitors under static conditions. The major differ-

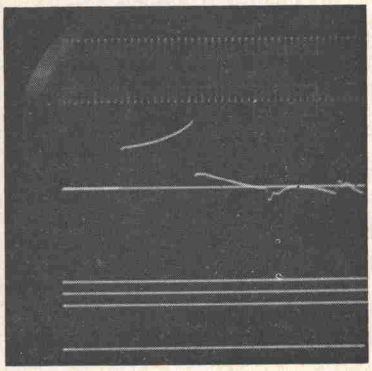

FIG. 3. Typical current-time record from small diameter-to-thickness disk. The disk was ½ in. in diameter and ¼ in. in length. Shot H-56B time increases from left to right. 10-Mc/sec timing wave.

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[10] R. A. Graham, G. E. Ingram, and W. D. Ingram, Sandia Corporation Research Report SC-4652 (RR) (November 1961).

[11] S. Thunborg, G. E. Ingram, and R. A. Graham, Rev. Sci. Instr. **35**, 11 (1964).

[12] G. E. Ingram, Rev. Sci. Instr. **36**, 458 (1965).

[13] Because the outer electrode region is not in a one-dimensional state, the current from the outer electrode suffers distortion similar to the bounded gauge distortion. Therefore, the potential on the two electrodes cannot be matched for all times. This does not have a significant effect on the field of the inner electrode region since the electric field corresponding to the potential difference between the electrodes is very small relative to the piezoelectric fields from the wavefront to the electrodes.

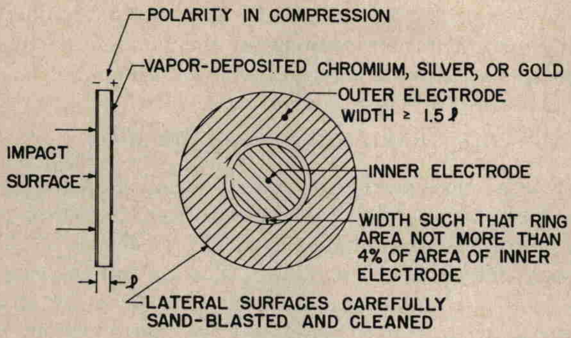

FIG. 4. Guard-ring configuration to obtain one-dimensional conditions.

ence in the dynamic case being considered here is that the traversing shock wave divides the disk into two regions of different field amplitudes whose lengths are time dependent. Hence, each region, the stressed and unstressed, has a different capacitive fringing factor and different time variation in the fringing factors. The guard ring eliminates this distortion by restricting the observation to the central region of the disk where there is negligible fringing.

As the wave moves along the disk in the axial direction, the boundary conditions require that shear and dilatational waves be formed immediately behind the wavefront at the lateral edge of the disk. These unloading waves then propagate laterally inward. Regions of the disk that experience these unloading waves from the lateral boundary are no longer in a state of one-dimensional strain. The central region of the disk will be in one-dimensional strain for the first wave transit time if the width of the outer electrode is such that an unloading wave does not reach the central region during first wave transit time.

However, since the medium is piezoelectric, the unloading waves change the polarization. To maintain constant electric displacement the electric field must also change. Field fringing would then be expected to occur from this unloading field and at any time the region of distorted field will be advancing radially inward in advance of the position of the unloading wave itself. Because of the anisotropy, no quantitative prediction was made of the width of outer ring required to take observations in one-dimensional field regions. However, we have empirically determined that the width of the outer ring must be no less than 1.5 times the thickness of the disk to completely eliminate this distortion during the first wave transit of a given stress amplitude.

The thin circular insulating ring cut through the electrode to form the inner and outer electrodes causes a local field distortion and an uncertainty as to the effective electrode area. In our experiments the width of the insulating ring was such that the area in the ring was from 2%–4% of the area of the inner electrode. Various ring widths in this range had no apparent effect on current from the disk. The small uncertainty in area due to the ring is calibrated into the guard-ring for disks constructed with rings whose width is in the range given above. Error is introduced if rings with large widths are used. The width of this ring cannot be easily reduced to less than 0.001–0.003 in. because a finite distance is required for dielectric strength between the two electrodes.

The features of a properly constructed guard-ring configuration are summarized in Fig. 4. Details of the proper construction of a guage, as given in Ref. 2, should be carefully followed.

GUARD–RING CURRENT COEFFICIENT

A typical guard-ring record is shown in Fig. 5 along with a definition of terms used in the data summary given in Table I. One should contrast this record with that shown in Fig. 3 to appreciate the distortion obtained with the fully electroded disk. However, even the current from the guard ring is observed to increase slightly as the wave propagates through the disk. It is shown in the Appendix that finite strain, an increase in dielectric permittivity with stress and electric field amplitude, and piezoelectric coupling will cause the current to increase linearly in time. The extent of the effect depends largely upon the stress amplitude. The current rise during transit time due to finite strain may be accurately calculated and is 4.8% at 20 kbar. The observed current rise of about 7% at 20 kbar shown in Table I (column 5) may be accounted for by the strain, an electromechanical coupling effect of 0.9%, and an increase of 0.6% in the dielectric permittivity of the stressed quartz.

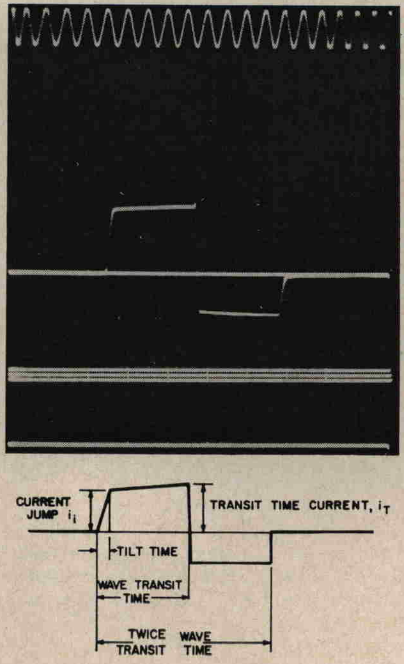

FIG. 5. Typical inner electrode guard-ring record and definition of terms. Time increases from left to right. 10-Mc/sec timing wave. Shot H-71.