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INVESTIGATION OF THE CHARACTERISTICS OF CERAMIC
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INVESTIGATION OF THE CHARACTERISTICS OF CERAMIC CAPACITORS FOR SYNCHROTRON KICKER-MAGNET APPLICATION*

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The inherently low inductance, geometrical simplicity, and low manufacturing costs of ceramic capacitors make them attractive for kicker-magnet pulse lines, but their piezoelectric and dielectric hystereses complicate their use. The piezoelectric characteristic causes mechanical fracture of the ceramic if the electrical gradient is too high; the dielectric hysteresis limits the repetition rate because of the associated temperature rise. Sensitivity of the capacitance to voltage and temperature does not appear to present a serious problem in this application, because the permissible gradient and temperature is limited by the other factors affecting reliability. These characteristics were measured for the most commonly used ceramics, and the results tabulated. From these data one can choose the best ceramic composition. The choice depends upon the repetition rate, pulse shape, and geometrical considerations of the capacitor. This study shows that properly designed ceramic capacitors are superior to other types for a kicker-magnet pulse line when the pulse length is sufficiently long to preclude use of a distributed line and when the rise and fall times are sufficiently short to make lead inductance significant.

Introduction

The rise and fall time of a pulse line is determined primarily by the cutoff frequency of the line. The pulse length is determined by the velocity of propagation and the electrical length of the line. Very high cutoff frequencies can be achieved by means of distributed lines such as coaxial cables; however, because of the high velocity of propagation and the dispersion of the pulse by the cable losses, this technique does not lend itself well to long pulses. Lumped-constant lines using oil, paper, or mica capacitors can be built with very low velocities of propagation, and lend themselves well to the generation of long pulses, but it is costly to achieve a high cutoff frequency with this technique. Combinations of distributed and lumped-constant lines have been used for kicker magnets in order to achieve fast rise and fall times with long pulses,¹ but this

*Work done under the auspices of the U. S. Atomic Energy Commission.

1. E. B. Forsyth, "The Fast Kicker of the AGS External Beam System," Brookhaven National Laboratory Accelerator Dept. (AGS) Internal Report EBF 3, October 27, 1964.

results in an impedance mismatch for those frequencies near and above the cutoff frequency of the lumped-constant line. The resulting reflection causes a perturbation on the pulse.

We have been studying a technique using ceramic capacitors that appears to better solve the problem of generating pulses with fast rise and fall times with long pulse lengths. The pulse-line sections are assembled on etched circuit boards--building the section capacitance from a matrix of small ceramic capacitors. A very large number of sections of pulse line can be assembled in a comparably small space. This results in a very high cutoff frequency and a very low propagation velocity. In one design, 24- by 36-in. etched circuit boards were used, and two sections of the pulse line were mounted on each circuit board. The capacitor consisted of 4-kV ceramic capacitors connected in a 10×56 matrix. Thirty such boards were used, resulting in a 60-section pulse line operating at 40 kV.

Our first attempts at pulse lines with ceramic capacitors resulted in inadequate capacitor life. Failure was caused by vibrational pulses within the ceramic caused by the electromechanical coupling. This problem has been investigated by Goodman.² We found that by operating the capacitors at lower electrical gradients, adequate life could be achieved.

Contact with the research departments of several capacitor manufacturers indicated to us that there was not sufficient information available on the ceramics to properly design them into pulse lines. Their ferroelectric, piezoelectric, and electrostrictive properties are quite unlike the dielectric characteristics of oil, paper, or mica capacitors which have been so widely used in pulse lines.

Electromechanical Properties of Ceramic Capacitors

The ceramic wafers used in these studies were supplied to us by the Centralab Corp., Milwaukee, Wisconsin. A dozen samples of each of 15 different ceramic compositions, representing all of the ceramics used by this Company were obtained for these tests. Each wafer is 0.5-in. in diameter and 0.1-in. thick. For each

2. G. Goodman, J. Appl. Phys. 35, 2725 (1964).

sample we measured the change in thickness as a function of the electric field. Equipment for this purpose was made available to us by Prof. Fulrath of the Division of Ceramic Engineering of the University of California, Berkeley.

We found that some ceramics were predominantly electrostrictive, but most were predominantly piezoelectric. Some showed a combination of the two. The distinction between the two types of couplings is based upon the behavior of the strain-versus-electrical-gradient curve in the vicinity of the origin; if the strain does not change sign as the electrical gradient does, the coupling is said to be electrostrictive. If the strain and electric field change sign together, the coupling is said to be piezoelectric. Typical examples of the two curves are shown in Fig. 1. Similar curves were obtained for all samples. Under ideal circumstances the strain-versus-electric-field curve of the piezoelectric material will be linear over a wide range of fields, whereas the curve for electrostrictive materials will be parabolic.

Since the electromechanical coupling coefficient is associated with the electric field to the first power in one case and to the second power in the other, it is misleading to compare the two coefficients directly when comparing different materials. Also, one must be careful in comparing two ceramics with different dielectric constants. The criteria for comparison should be based upon equal energy density; thus a dielectric with a high dielectric constant will be operated at a lower electrical gradient than one of lower dielectric constant. To circumvent the difficulty associated with the two types of electromechanical coupling, we feel that the strain can be compared at the gradient corresponding to maximum permissible energy-storage density.

From a life test for one of the ceramics, T 22, we found that a satisfactory maximum operating energy is 8.81 kJ/m^3 . We calculated an electric field to produce this energy density in each of the ceramics, and then tabulated the displacement measured in this field in Table I. In general, those ceramics showing some electrostrictive properties have lower strain than the piezoelectric ceramics.

Power Dissipation in the Ceramic

Power is dissipated in the ceramic because of the area of the dielectric hysteresis loop and because of ohmic resistance of the ceramic. At the usual operating temperatures the power dissipated in the ohmic resistance is negligible. However, above 120°C it becomes appreciable for some ceramics. We obtained dielectric hysteresis curves for all ceramic samples; a typical curve is shown in Fig. 2. The hysteresis curves of each of the ceramics was displayed on an oscilloscope, photographed and enlarged. The area of the curve was measured with a planimeter. The dissipation factor, defined as the energy loss per cycle divided by the energy

stored, was computed for each of the ceramics at four different temperatures at an electric field of 44 V/mil . The results are tabulated in Table I. The dissipation factor decreases with increasing temperature in each case; this makes the capacitor temperatures self-regulating, i. e., as the temperature increases the dissipation decreases until equilibrium is reached. Our experience indicates that power dissipation is not a limitation at a repetition rate of 60 pps, but it clearly would be if the repetition rate is increased sufficiently.

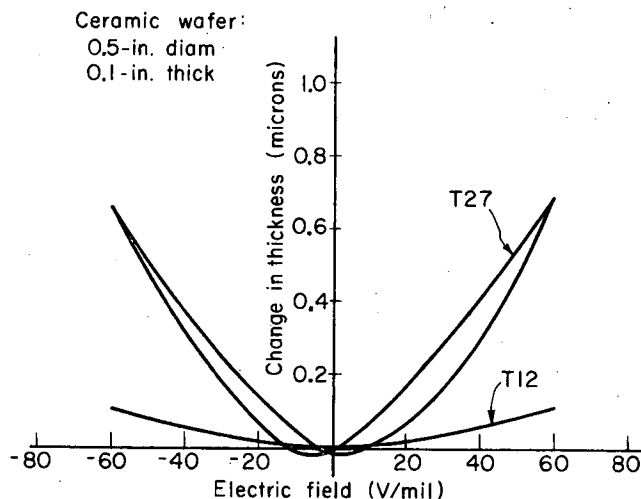
Other Observations

1. In general, the twelve samples in each batch were quite uniform in characteristics, the precision of our measurements were within about 5%.

2. Large signal-dissipation factors are orders of magnitude higher than those for small signals and decrease with increasing temperature until the curie temperature is reached.

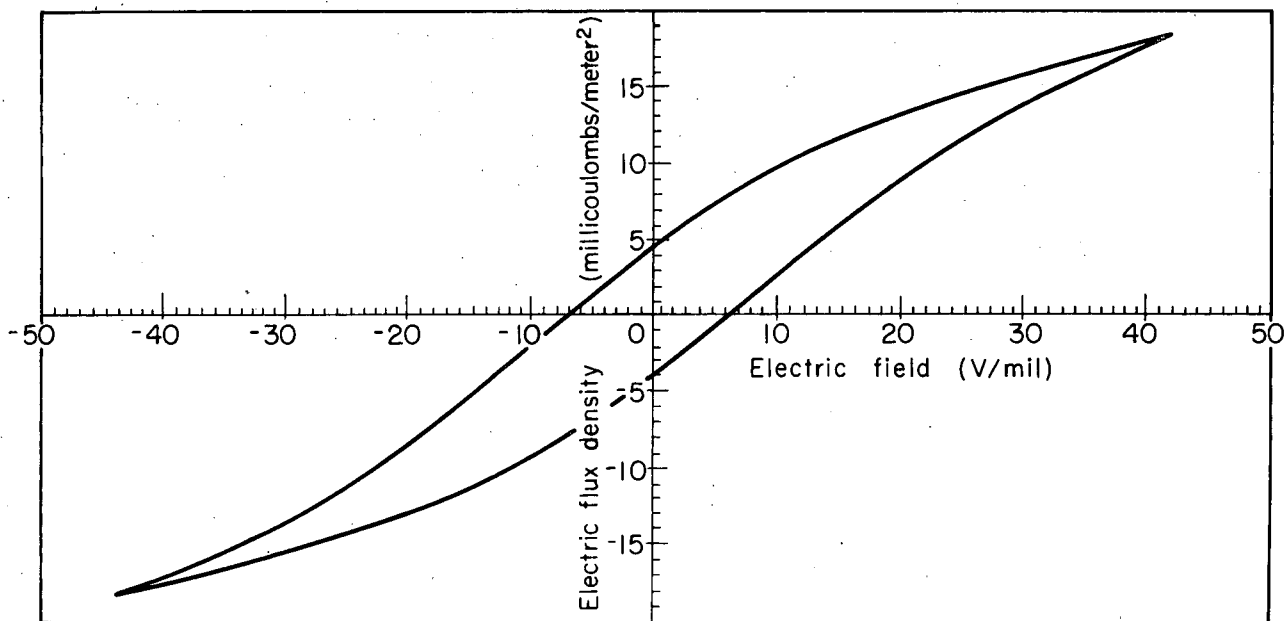
3. At a certain characteristic electric field, different for each ceramic, the hysteresis loop begins to open as the field increases. Below this value, no width of the hysteresis loop was observable within the resolution of our equipment. Above this threshold the dissipation factor climbs rapidly. However, for sinusoidal excitation extending from three to five times threshold, the dissipation factor is nearly what it is at maximum applied field. The threshold seems to be above 2 to 7 V/mil.

4. For some samples considerable dc leakage developed in the ceramic about 120°C .



XBL692-1953

Fig. 1. Strain vs electric field for two types of ceramic capacitors. Type T-27 is a typical piezoelectric ceramic and T-12 is a typical electrostrictive ceramic. Curves of this type were obtained for all of the ceramics shown in Table I.



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Fig. 2. Dielectric hysteresis loops for type T-27 ceramic at 26°C. Loops of this type were obtained for all of the samples. The dissipation factors shown in Table I were obtained from planimeter measurements of the loop areas. The reduction in loop area and losses with increasing temperature produces an automatic temperature regulation of the capacitors.

Table I. Ceramic capacitor data.*

Mfg. No.	Type [†]	Deformation	Dielectric constant	Deformation coefficient		Dissipation factor [‡]				Curie temp. (°C)	Estimated [§] operating field (V/mil)	Deformation at operating field per unit change in thickness (10 ⁻⁵ in./in.)
				a in./V ×10 ⁻⁹	b in. ² /V ² ×10 ⁻⁹	20°C	50°C	100°C	150°C			
T4	A	Electrostrictive	740		0.9	0.24	0.19	0.06	0.25	120	30.4	1.4
T11	A	Piezo.+electro.	1070		1.4	0.13	0.01	<0.01	0.46	50	26.8	1.2
T12	A	Piezo.+electro.	1500	0.4	0.5	0.07	<0.01	<0.01	<0.01	40	22.2	1.25
T14	A	Piezo.+electro.	640	0.5	0.2	0.25	0.17	0.02	0.28	110	33.7	1.80
T15	C	Electro.	780		0.9	0.23	0.19	0.09	0.12	120	30.4	1.03
T18	C	Piezo.+electro.	1450	0.3	1.7	0.31	0.21	0.09	0.12	120	22.6	1.3
T21	A	Piezo.	2220	1.3		0.04	<0.01	<0.01	0.21	35	18.0	1.65
T22	C	Piezo.	1780	3.2		0.43	0.34	0.09	<0.01	120	20.6	4.1
T26	B	Piezo.	1870	3.7		0.36	0.27	0.08	<0.01	120	20.1	5.1
T27	C	Piezo.	1860	4.0		0.44	0.35	0.12	<0.01	120	20.0	4.9
T32	B	Piezo.	3410	5.3		0.36	0.22	<0.01	<0.01	90	14.9	6.8
T51	A	Piezo.	4650	6.1		0.23	0.09	<0.01	<0.01	70	12.5	8.5
T63	A	Piezo.	7650	7.6		0.22	0.07	<0.01	<0.01	70	9.8	8.2
T66	A	Piezo.	6800	6.6		0.29	0.10	<0.01	<0.01	70	10.2	9.0
T82	A	Piezo.	9300	7.4		0.22	0.06	<0.01	<0.01	70	8.9	6.3

* 0.5-in.-diam., 0.1-in.-thick ceramic samples supplied by Centralab Corporation, Milwaukee, Wisconsin.

[†] Group A: Greater than 60% alkaline-earth-oxide-modified barium titanate.

Group B: Greater than 60% rare-earth-modified barium titanate.

Group C: Greater than 60% bismuth-modified barium titanate.

[‡] Large signal: 44 V/mil.

[§] Corresponding to a stored energy density of 8.71 KJ/m³.

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