MASTER

MEASUREMENT OF FAST RISETIME MEGAMPERE CURRENTS BY QUARTZ GAUGE*

R. E. Williams, D. H. McDaniel and R. W. Stinnett
Sandia National Laboratories, Albuquerque, New Mexico 87185

Abstract

Quartz gauges have been used on the Sandia National Labortories Proto II accelerator to measure current in the magnetically insulated transmission line at the 11 TW power level. The accelerator delivers 3.5 MA at 2×10^{14} A/s in a 40 ns pulse to a 0.0127 m diameter aluminum liner to produce a high density plasma. At this radius and dI/dt levels, the B-dot monitors no longer function for the measurement of load current because the monitor suffers electrical breakdown. Quartz pressure gauges mounted at a radius of 0.0086 m have sucessfully measured the magnetic pressure due to the load current with nanosecond temporal resolution.

The quartz gauge is mounted 5×10^{-4} m under the electrode surface and hence the current carrying surface is not perturbed by the gauge itself. The surface material is chosen so that its yield strength is greater than the pressure exerted by the magnetic field. Hence, the pressure pulse is not affected by the material properties of the wall as it propagates to the quartz gauge. For this case, only the piezoelectric and material properties of the quartz are needed to infer pressure from the gauge output. The current output in amperes from the quartz gauge is given in terms of the stress-σ in Pascals, transit time through the gauge-t_o in seconds and the gauge area-A in m^2 by the equation[1]

$$I = (2.011 \times 10^{-12} + 1.1 \times 10^{-22}\,\sigma)\;\sigma A/t_o.$$

Measurements can be extended to current and pressure levels where the yield strength of the wall material is exceeded, but the analysis of the gauge signal is more complicated. Gauge design requirements and experimental results will be discussed.

Introduction

The Proto II accelerator, at Sandia National Laboratories, delivers a power of 11 TW and a current rate of change of dI/dt of 4×10^{14} A/s. The power flows down a self-magnetically insulated transmission line to a 1.2×10^{-2} m diameter aluminum liner on the axis of the accelerator. This liner produces a high density plasma. The rate of change in the magnetic induction at the surface of the liner is $dB/dt = 6 \times 10^{9}$ T/s. At this level of dB/dt measurements of current in the magnetically insulated transmission line can not be made using conventional B-dot techniques. Figure 1 shows a conventional method of using a "grooved B-dot" for measuring current. A 50 Ω coaxial cable measures the voltage across the groove induced by the changing magnetic flux within the groove. We have found that at 2 MV/m the current no longer flows along the surface of the groove but bridges the gap and causes not only loss of the electrical signal in the 50 Ω cable but the breakdown of the magnetically insulated transmission line. The breakdown level was determined by varying the groove dimension and radial position and observing when the signal was lost. The electric field across the groove is given by

$$E = \frac{L_g}{\Delta r}\frac{dI}{dt} \qquad (1)$$

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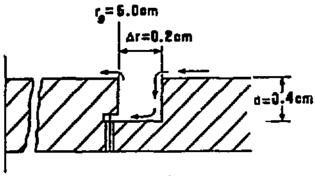

Fig. 1. A typical grooved B-dot current measuring configuration.

where Δr is the width and L_g is the inductance of the groove. The inductance of the groove is given by

$$L_g = 2 \times 10^{-7}\, d\, \ln(1 + \Delta r/r) \qquad (2)$$

where d is the depth of the groove and r is its radial position. By expanding the log term to first order with Δr << r we have

$$L_g = 2 \times 10^{-7}\, d\, \Delta r/r \qquad (3)$$

Substituting this into (1), we find

$$E = \frac{2 \times 10^{-7}}{r}\, d\, dI/dt \qquad (4)$$

Hence, with the criterion that $E \leq 2 \times 10^{6}$ V/m we have

$$\frac{d}{r} \leq \frac{10^{13}}{dI/dt} \qquad (5)$$

To measure the current at $r = 10^{-2}$ m, which is close to the load of the magnetically insulated transmission line, the depth of the groove for a dI/dt of 2×10^{14} A/s would have to be less than 5×10^{-4} m. Hence, the difficulty of this type of current measurement is apparent. At slightly higher dI/dt's these grooves cause breakdown within the magnetically insulated transmission lines.[3] We have also determined experimentally that 3.2×10^{-3} m diameter holes in the transmission line containing individual B-dot loops lead to magnetic insulation breakdown.

Magnetic Pressure Measurement

A measurement technique is needed which monitors the current in the transmission line and which does not perturb the conductor's front surface. The current flowing in a radial transmission line has an associated mechanical pressure

$$P = B^2/2\mu_o = \mu_o I^2/8\pi^2 r^2 \qquad (6)$$

A quartz pressure gauge, if placed behind the electrode surface of the transmission line, can directly monitor this pressure. This configuration, shown in Fig. 2,

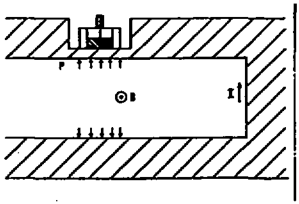

Fig. 2. The configuration for measuring the magnetic pressure due to the current flow.

allows the front surface of the transmission line conductor to be completely free of perturbations provided the gauge is a few times deeper that the electrical skin depth.

Shock pressure measurement in materials is an extensively documented technology.[2] A typical pressure measurement assembly, shown in Fig. 3, consists of a circular piezoelectric quartz disk bonded to a section of metal. The single crystal quartz is gold plated on opposing flat surfaces. The top surface has two separate electrodes. The inner electrode collects charge from an area designed to see a one dimensional stress wave and connects to a 50 ohm coax cable for instrumentation. The outer electrode forms a guard ring and is electrically loaded to pass the same current per-unit area as the center electrode (Fig. 3). This electrode is needed to minimize edge effects due to the finite gauge size.

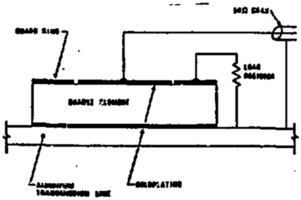

Fig. 3. The quartz gauge pressure measurement assembly.

When a plane pressure wave is applied to the front surface of the piezoelectric quartz element, a current I_g immediately flows in to the load resistors according to the equation[1]

$$I_g = (2.01 \times 10^{-12} + 1.1 \times 10^{-22} \sigma)\,\sigma A/t_e \qquad (7)$$

Where t_e is the transit time of the pressure wave through the gauge in seconds, A is the area in square meters, σ is the pressure in Pascals and I_g is the gauge current in amperes. The current continues to flow until the pressure wave reaches the back surface of the gauge. This equation is valid for pressures up to 3.0×10^9 Pascals. The pressure wave travels at a velocity of 5.7×10^3 m/s. Hence the useful recording time of the gauge is the gauge thickness divided by this velocity. During this transit time of the pressure wave through the gauge the output current of the gauge follows the input pressure with a nanosecond response time. At the same time that the pressure wave propagates through the quartz, a relief wave propagates inward at a 45° angle from the edge of the gauge. The portion of the gauge affected by the relief wave is covered by the guard ring, and hence the relief wave is not seen by the instrumented electrode.

The sensitivity of the gauge can be controlled by changing of the material stack impedance in front of the gauge. The pressure P_Q in the quartz gauge behind the metal surface is related to the pressure P_M in the metal, and the shock impedances of the quartz and metal Z_Q and Z_M, respectively, by

$$P_Q = (2Z_Q P_M)/(Z_Q + Z_M) \qquad (8)$$

By using metals with a higher yield strength than the applied pressure, this measurement technique can be extended to higher pressures without resorting to a more complicated analysis than that given by equation 1.

Gauge Mounting Considerations

Since the quartz gauge requires a uniform pressure pulse to be incident on its front surface, the mechanical tolerances of the surface finish and thickness are very important. At a material velocity of 6×10^3 m/s a difference of material thickness in front of the gauge of 2.54×10^{-5} m corresponds to a difference in arrival time of 4×10^{-9} seconds. When one is trying to resolve current risetimes on the nanosecond time scales, mechanical tolerances are obviously very important. Hence the quartz gauges are mounted on flat *surfaces that are parallel to the current carrying surface.* The geometry in which the gauge is used must allow spatially uniform (3 percent) pressure over the gauge front. Gauge bonding to the surface is usually done with pressure cured epoxy. Surface finishes are typically 2.5×10^{-8} meters. The mounting procedure should not perturb the flatness of the surface. Another concern of magnetically insulated transmission line gauges is that the anode material in front of the gauge has to be sufficiently thick to stop electrons crossing the vacuum gap. If these electrons penetrate into the gauge a signal resembling that of a Faraday cup will be obtained.

Experimental Results

Initial experiments used four 6.35×10^{-3} m diameter quartz gauges with two located at 0.0254 m radius and two located at 0.0508 m radius. These gauges are 5×10^{-4} m thick which allows a recording time of 100 ns. Figure 4 shows the gauge output signals as a function of time for a Proto II test. The signals rise to peak pressures of 1.3×10^8 Pascals for the gauges at 0.0254 m radius and a pressure of 3×10^7 Pascals for the gauges at 0.0508 m radius in 20 ns. The abrupt signal fall occurs at the end of the gauge recording time. The pressure between these two positions did not vary as r^{-2} and indicates that current losses occurred between these two positions. The losses were verified by Faraday cup measurements. A comparison between the current measured at 0.72 m using B-dot loops to the current measured at the 0.0508 m radius is shown in Fig. 5. The rise times agree with an indicated current loss at peak current between these two positions.

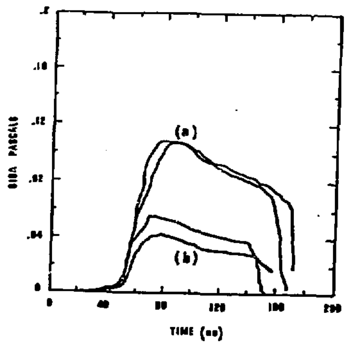

Fig. 4. Quartz gauge traces for a radius of (a) 2.54×10^{-2} m and (b) 5.08×10^{-2} m.

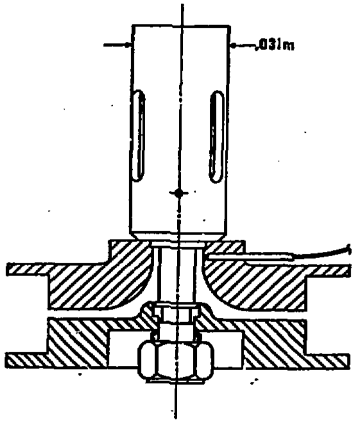

Fig. 6. Position of the 2.8×10^{-3} m diameter gauge located at 8.6×10^{-3} m radius.

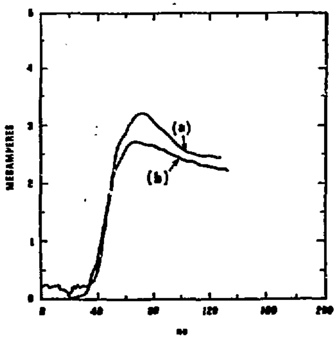

Fig. 5. A comparison between the quartz gauge signal and the B-dot signal.
a. B-dot located at r = 0.72 m.
b. Quartz gauge located at $r = 5.08 \times 10^{-2}$ m.

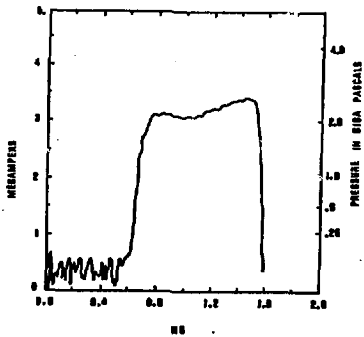

Fig. 7. Current and pressure as measured by the 2.8×10^{-3} m diameter quartz gauge at a radius of 8.35×10^{-3} m.

Figure 6 shows a quartz gauge mounted to measure the current flowing in the load at a radius of 8.35×10^{-3} m. This quartz gauge had a diameter of 2.8×10^{-3} m and a thickness of 5×10^{-4} m. The experimental results are shown in Fig. 7. A peak pressure of 2.5×10^{9} Pascals, which corresponds to a current of 3.5 MA in the load was measured. The quartz gauge current waveform is consistent with the measured liner dynamics and the assembled plasma properties.

Conclusions

Quartz gauges have successfully measured magnetic pressure due to a large load current at a small radius. These gauges may be attached to a current carrying conductor without producing electrode surface perturbations. Care in design of the electromechanical assembly is necessary, but using quartz gauges is no more difficult than the more conventional current measuring technique. The gauge has nanosecond frequency response. This technique is extendable to higher current by using hydrodynamic codes to analyze the pressures.

References

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