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APPLICATION OF PIEZOELECTRIC STRESS GAUGES TO THE MEASUREMENT OF FAST-RISE-TIME MULTIMEGAMPERE ELECTRIC CURRENTS

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Modeling of load behavior in Z-pinch plasma radiation sources driven by high current generators requires accurate measurement of fast-rise-time multimegampere electrical currents close to the load. Using a novel application of high pressure technology, we have demonstrated that fast-response piezoelectric stress transducers can measure such currents under conditions of extremely high current density, induced electric fields, and bremsstrahlung radiation where conventional current diagnostics fail. Large signal, nanosecond-time-resolution lithium niobate piezoelectric stress gauges are employed to directly measure the magnetic pressure $B^2/2\mu_0 = \mu_0 I^2/8\pi^2 r^2$ generated at radius r by a current I flowing in a radial transmission line near the load of a pulsed power current source. With a current diagnostic consisting of a pure tungsten electrode on a Y-cut lithium niobate stress gauge, current densities up to $I/2\pi r = 78 \text{ MA/m}$ can be measured before the electrode yield strength and piezoelectric operating stress limit are exceeded. Based on this work, we have developed a compact modular current probe for use on the high current (20-25 MA) DECADE simulator being constructed for the Defense Nuclear Agency. We also describe recent work extending this measurement technique to higher current densities (125 MA/m) using a copper-sapphire electrode impedance stack on an X-cut quartz piezoelectric element.

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INTRODUCTION

In recent years, intense pulsed x-ray sources have been developed [1] which utilize pulsed power drivers delivering multimegampere electric currents to radially implode a hollow cylinder of ionized gas, a cylindrical foil, or wire array. Accurate current measurements close to the load are required to model the implosion dynamics and radiation production physics of the source. Standard Rogowski coil and B-dot loop current monitors are unreliable when used closer than about 5 cm to the load on large accelerators because of electrical failure resulting from large electric fields induced across the monitor housing when a conducting plasma is present.

To avoid these difficulties, we have developed a noninductive, nonperturbing current diagnostic [2] consisting of a miniature piezoelectric stress gauge which directly measures the magnetic pressure generated by the load current in the transmission line wall. We have extended this technique originally suggested by Williams et al. [3], by using high yield strength W electrode disks and sensitive lithium niobate (LiNbO_3) piezoelectric elements to provide sufficient signal amplitude for accurate current measurements up to current densities of $I/2\pi r = 78 \text{ MA/m}$ in the harsh electrical noise environment of PROTO-II (5.5 MA peak current) and the much larger SATURN accelerator (10 MA peak current) at Sandia National Laboratories. We have also recently developed modular stress gauge current probes to permit rapid, accurate current measurements on the DECADE weapons effects simulator (20-25 MA peak current) now under construction for DNA. With a different combination of electrode and transducer materials, we have extended this measurement technique to a higher current density limit of 125 MA/m.

CURRENT MEASUREMENT TECHNIQUE

The current flowing in a magnetically insulated transmission line (MITL) can be determined directly from the magnetic pressure generated by the load current. For a radially symmetric MITL feed, the magnetic field for a total current I flowing at radius r is $B = \mu_0 I / 2\pi r$. The magnetic pressure exerted on the transmission line wall is then given by:

$$P_M = \frac{B^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 r^2} \quad (1)$$

At high current density and dI/dt , where inductive current monitors fail, this pressure pulse can be easily measured with nanosecond time resolution using an appropriate piezoelectric stress gauge.

We have demonstrated the effectiveness of this concept by performing a series of current measurements very near the gas puff load on the PROTO-II and SATURN accelerators at Sandia, using compact stress gauges of high sensitivity [2]. The basic construction of the stress gauge current diagnostic is shown in Fig.1. A piezoelectric stress gauge is bonded to a metal electrode disk which forms an integral part of the transmission line wall. Thus, the stress gauge is mounted behind a continuous conducting surface several times the electrical skin depth in thickness and does not perturb the current flow. Dimensions of the piezoelectric element are chosen so that the active instrumented area of the gauge sees only a uniaxial stress wave during the transit time of the wave through the piezoelectric disk.

The response of piezoelectric stress gauges of this type has been characterized for a number of electrode configurations and impulsive shock loading conditions [4,5]. For a uniaxial stress wave σ_T (Pa) applied to the front surface of the piezoelectric element, the transducer responds with subnanosecond time resolution by generating

a current $i_T(A)$ in the load circuit which is directly proportional to the stress at the front electrode for times less than the transit time of the element. The resulting voltage across the load resistor $R(\Omega)$ is given by:

$$V_T = Ri_T = \frac{RkA\sigma_T}{t_0} \quad \text{for } t < t_0 \quad (2)$$

where $k(C\ m^{-2}\ Pa^{-1}, C\ m^{-2}\ Pa^{-2})$ is the piezoelectric constant of the gauge material relating induced polarization to the applied stress, $A(m^2)$ is the gauge active area, $\sigma_T(Pa)$ is the stress on the front surface of the piezoelectric element, and t_0 is the transit time of the stress wave through the gauge. An impedance mismatch exists at the electrode-piezoelectric interface. The stress σ_E of the incident wave at the back of the metal electrode is related to the stress σ_T at the front of the piezoelectric transducer by:

$$\frac{\sigma_E}{\sigma_T} = \frac{Z_E + Z_T}{2 Z_T} \quad (3)$$

where Z_E and Z_T are the mechanical shock impedances of the metal electrode and piezoelectric disk, respectively. If an electrode material is chosen whose yield strength is greater than the peak applied pressure, then the current-generated stress wave will propagate elastically, and we can equate the magnetic pressure P_M with σ_E at the back of the electrode. Under these conditions, the current line density $I/2\pi r(A/m)$ flowing in the transmission line at radius $r(m)$ is given in terms of the measured stress gauge voltage $V_T(V)$ as:

$$\frac{I}{2\pi r} = \left[\frac{2}{\mu_0} \left(\frac{Z_E + Z_T}{2 Z_T} \right) \left(\frac{t_0}{RkA} \right) \right]^{1/2} V_T^{1/2} \quad (4)$$

A problem of particular concern for all current measurements on a high-current driver

such as SATURN is the interaction of prompt high energy (>100 keV) bremsstrahlung radiation from the load region with the current diagnostic and signal cable. The stress gauge current diagnostic is unique in the sense that interference from source-generated bremsstrahlung noise can be eliminated in a straightforward way by providing adequate propagation time delay in the electrode layer to separate the prompt bremsstrahlung noise from the current-induced stress wave to be measured.

Piezoelectric materials tested included X-cut quartz, and Z-cut, Y-cut, and positive- 36° -rotated Y-cut lithium niobate (LiNbO_3), with Ni and W electrode layers. Piezoelectric constants and other relevant parameters for these materials are summarized in Ref. 2. The most effective current stress gauge developed from this family of materials consisted of a pure W electrode, with a Hugoniot elastic limit of 3.77 GPa [6], on a Y-cut LiNbO_3 piezoelectric element. The primary advantage of LiNbO_3 over X-cut quartz for measurements with compact gauges at moderate current densities (<50 MA/m) is the much higher sensitivity (10-20) of LiNbO_3 and the improved impedance matching of LiNbO_3 with electrode materials of higher yield strength than Al [7,8]. Y-cut LiNbO_3 has a relatively high sensitivity and the highest operating stress limit (1.8 GPa) of the three crystal orientations of LiNbO_3 . Both the yield strength of W and the limiting operating stress of Y-cut LiNbO_3 impose a limitation on the maximum current density which can be measured of $I/2\pi r = 78$ MA/m [2].

The accuracy of the LiNbO_3 gauge current measurements was evaluated by comparison with other current diagnostics at large radius on shots where feed losses between diagnostics were judged to be small. Fig. 2 shows the results of a current measurement on a SATURN shot with a low-inductance short-circuit load. The reflection of the stress wave at the back surface of the piezoelectric element is marked by a sharp drop

in the stress gauge signal (Fig. 2a). The recording time of the gauge, defined by the transit time t_0 of an elastic wave through the piezoelectric disk, is chosen to be longer than the risetime of the current pulse. Fig. 2b shows the excellent agreement between current waveforms derived from the LiNbO₃ stress gauge current measurement at $r = 2.0$ cm and calibrated B-dot current monitor measurements at $r = 5.24$ cm. Fig. 3 shows a comparison of current waveforms derived from a LiNbO₃ gauge signal at $r = 2.54$ cm, a Faraday rotation current diagnostic [9] at $r = 6.0$ cm, and an uncalibrated B-dot loop current monitor at $r = 5.24$ cm. The stress gauge current agrees well in both shape and amplitude with the current from the Faraday rotation diagnostic, and in shape with the B-dot monitor, until just after peak current. At that time, an ablation pressure pulse generated in the electrode surface by x-ray energy deposition from the Z-pinch x-ray source appears on the stress gauge waveform.

MODULAR CURRENT PROBES FOR DECADE

We have developed a compact modular piezoelectric current probe [10] to provide routine high-current density measurements on the DNA DECADE simulator (20-25 MA peak current) now under construction. The basic probe design again uses a W overlayer on a Y-cut LiNbO₃ piezoelectric element. The linear current density limit of 78 MA/m for this configuration restricts current measurements to $r \geq 5.1$ cm for $I = 25$ MA. The recording time of the gauge is 250 ns to accommodate a 200 ns long current pulse. The transit time delay in the W electrode is 292 ns, about twice the expected implosion time of 150 ns for a Z-pinch load on DECADE. At $I = 25$ MA and $r = 5.1$ cm, the peak signal is 36 V.

The DECADE modular current probe is designed in a compact package that can be easily

installed. The probe body (Fig. 4) is screwed into the transmission line wall and an indium gasket is extruded into the gap between the overlayer and wall to form a continuous electrical connection. A signal cable and shield cable can then be directly attached to threaded connectors on the end of the probe. Work is in progress to develop methods for individually calibrating each gauge. The acoustic delay of the overlayer and the recording time of the probe are accurately measured with a pulsed laser system.

During development, these modular probes were tested on the SATURN accelerator. Probes were mounted at $r = 3.8\text{-}4.8$ cm and generated good signals under all conditions. Signal waveforms and derived feed currents from a typical shot are shown in Fig. 5. The large negative signal near the beginning of the trace is prompt-bremsstrahlung-induced noise which is isolated from the positive polarity current-induced pressure pulse by propagation delay in the W electrode.

EXTENSION TO HIGHER CURRENT DENSITIES

To permit measurements of current densities greater than 78 MA/m, we have designed a stress gauge configuration with an electrode consisting of a skin-depth-thick (50 μm) conducting layer of Cu bonded to a thicker layer of sapphire (Al_2O_3), with an X-cut quartz piezoelectric element. The Hugoniot elastic limit of 60°-rotated Z-cut single-crystal sapphire may be as high as 20 GPa with a lower limit of 12 GPa [5,6], so that stress waves of much higher peak stress can propagate elastically in this overlayer than in W. X-cut quartz has a limiting operating stress of 4-5 GPa and low sensitivity is no longer a problem at high stress levels. Fig. 6 shows a TITAN hydrocode calculation of stress-time profiles in a Cu-sapphire electrode. Attenuation and distortion of the input

stress wave in the thin Cu conducting layer is minimized because negligible plastic work is required to shock-load this very low-yield-strength material. A 9.8-GPa peak surface stress is required to produce a 5.0-GPa (limiting) stress at the front of the X-cut quartz gauge. The peak-current-density limit for the Cu-sapphire electrode on X-cut quartz is 125 MA/m, or 20 MA peak current at $r = 2.54$ cm [2].

These copper-sapphire-quartz (CSQ) current monitors have been tested on foil implosion experiments on the SATURN accelerator. Fig. 7 shows a comparison of the MITL current derived from the signal of a CSQ gauge mounted at $r = 1.65$ cm (96 MA/m peak current) in a cylindrical wall immediately after a sharp bend in the MITL and the current from a W-LiNbO₃ gauge signal at $r = 3.61$ cm (42 MA/m peak current) measured on a smooth radial section of the feed. Typical of most measurements in this series, the two current waveforms show comparable peak currents, suggesting that the CSQ gauge is operating properly. However, the current from the CSQ gauge at small radius consistently shows a much faster risetime than the current from the gauge at large radius (25 ns vs. 65 ns), suggesting that current losses may be occurring early in the power pulse somewhere between the two gauges, probably at the sharp bend in the power feed.

At current densities above about 100 MA/m, the contribution to the transmission line surface pressure from heating and vaporization of the thin metal conducting layer can be significant and must be evaluated. For the range of current densities studied in the work described here, limits for transmission line surface ablation are not exceeded and this effect may be neglected.

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Figure 1. Schematic of the miniature piezoelectric stress gauge assembly mounted in a transmission line.

Figure 2. (a) Signal from a Y-cut LiNbO₃ stress gauge on a pure W electrode at $r = 2.13$ cm for SATURN shot 583 with a low-inductance short-circuit load. (b) Comparison of LiNbO₃ gauge current measurement and a calibrated B-dot current measurement at $r = 5.24$ cm on SATURN shot 583.

Figure 3. Comparison of LiNbO₃ stress gauge, Faraday rotation, and (uncalibrated) B-dot current measurements on a PROTO-II neon gas puff experiment.

Figure 4. Design of DECADE modular stress gauge current probe.

Figure 5. (a) Comparison of signals produced on a typical SATURN shot by two DECADE stress gauge current probes located 180° apart at $r = 4.4$ cm. (b) Total SATURN transmission line current derived from the stress gauge waveform shown in 5(a).

Figure 6. TITAN calculation of stress-time profiles in a Cu-sapphire electrode. Stress-time profiles are shown at the front ($d_1 = 0$ μm , solid line) and back ($d_1 = 35$ μm , dotted line) of the Cu layer, and at $d_2 = 1$ mm (dot-dashed line) and $d_2 = 1.82$ mm (dashed line) in the sapphire layer.

Figure 7. Comparison of MITL feed currents derived from a) Cu-sapphire-quartz current gauge measurement at $r = 1.65$ cm; and b) W-LiNbO₃ gauge measurement at $r = 3.61$ cm.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

SATURN SHOT #01522 09/25/92 10:15:58

FIG. 5 (a)

SATURN SHOT #01522 09/25/92 10:15:58

FIG. 5(b)

FIG. 6

IQXIN - CURRENT AT R = 1.65CM

25-JAN-92
1335.DAT

FIG. 7(a)

ILYOS - CURRENT AT R = 3.61CM

FIG. 7 (b)

25-JAN-92
1335.DAT

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