LA-10586-MS



Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

# Design of Pulse Transformers for Isolation Protection and Higher Speeds in the Remote Firing of Bridge Wires



Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

LA-10586-MS

UC-38
Issued: January 1986

13

# Design of Pulse Transformers for Isolation Protection and Higher Speeds in the Remote Firing of Bridge Wires

W. H. Bostick
B. L. Freeman
J. C. King
A. R. Martinez



Los Alamos National Laboratory
Los Alamos, New Mexico 87545

# DESIGN OF PULSE TRANSFORMERS FOR ISOLATION PROTECTION AND HIGHER SPEEDS IN THE REMOTE FIRING OF BRIDGE WIRES

by

W. H. Bostick, B. L. Freeman, J. C. King, and A. R. Martinez

ABSTRACT

The continued development of high-performance explosive pulsed power supplies has necessitated the development of high-voltage isolated x-unit systems. We have developed a circuit involving an x-unit, a step-up transformer, a pulse-forming network, a step-down transformer, and a bridge wire. With this circuit, the time to burst a single bridge wire was reduced from 0.6 μs for a direct, short x-unit connection to 0.21 μs while obtaining an x-unit-to-bridge wire isolation of $\geq$ 180 kV.

---

## I. RATIONALE AND MOTIVATION FOR EMPLOYING PULSE TRANSFORMERS IN THE CIRCUITS FOR FIRING BRIDGE WIRES

With the development of FCG's (magnetic flux compression generators) for high-power pulses at high voltage (~ 1-10 MeV) as well as at high current, it is necessary to have high-voltage insulated circuit elements between the explosive-initiation pulse generator (x-unit), which provides the pulse power for firing the bridge wires, and the bridge wires themselves. Also if the x-unit is to be protected from the effects of the high-explosive of the FCG, it should be provided with 50 to 100 ft of cable between itself and the bridge wires. The transmission of a fast-rising (~ $2.5 \times 10^{10}$ A/s) current pulse from a low-impedance x-unit ($C \simeq 50$ μf, $L \simeq 129$ nH, $\sqrt{L/C} = 0.05\ \Omega$) to 50 bridge wires in parallel, 100 ft distant from the x-unit cannot be accomplished with fidelity, efficiency, or safety with one 30-Ω C-cable (Reynolds

167-2669C), or with 50 such cables in parallel (30/50 Ω = 0.67 Ω). One of these cables with a length of 100 ft has a series inductance of 11 μH, compared with 129 nh = 0.129 μh of the x-unit. Fifty of such cables in parallel have an inductance of 0.22 μh. The impedance mismatch is severe; too much series inductance is introduced; and there is no circuit element to furnish high-voltage isolation.

The energy stored in the 50-μf capacitor of the x-unit at 2 kV is $1/2\ CV^2 = 100$ J. The energy required to fire one bridge wire attached directly to the x-unit through 5 ft of C-cable can be measured by evaluating

$$\int_o^{t_1} i^2 R dt$$

where it is assumed that R is a constant of 0.05 Ω, i is measured by a current-viewing resistor of 0.05 Ω, and $t_1$ is measured by the notch in the i-trace on the scope. Such a trace (Fig. 1), with 2 kV on the x-unit, gives a time $t_1$ when the wire turns to vapor and plasma of $\leq 0.6$ μs. At this time the current has risen to a value of $i_1 = 10^3$A, and the voltage across the resistance of the bridge wire is 50 V.

$$\int_o^{t_1} i^2 R dt = 0.01 \text{ J}$$

under these circumstances. In contrast, using a matching pulse transformer with the x-unit the bridge wire is fired at $t_1 = 0.25$ μs instead of at 0.6 μs, and the total energy (see Fig. 2),

$$\int_o^{t_1} i^2 R dt = 0.005 \text{ J} \quad ,$$

is reduced to about one-half of the energy required for slower operation.

Since the energy required to fire a bridge wire is such a small fraction of the energy stored, it is unwise to make efficiency the first priority in designing the circuit. High-voltage isolation and speed, or time minimization, are considered to be the more important parameters in this instance.

## II. EVOLUTION OF A HIGH-VOLTAGE ISOLATED FIRING CIRCUIT WITH AN IMPROVEMENT IN SPEED OVER THE SIMPLE X-UNIT

Figure 3 gives a schematic of the circuit that has evolved: capacitor $C_B$ is composed of 14 barium-titanate, 500-pf capacitors (30-kV rating) in parallel:

$$C_B = 7 \times 10^{-9} f.$$

Transformer A ($n_{AP}$ = 1 turn, $n_{AS}$ = 10 turns) is wound on the core shown in Fig. 4. The coils are wound on the central leg which has an area A = 39 $cm^2$. Each coil is made of two layers, five turns each, connected in series for the high-voltage winding. The low-voltage winding of each transformer is effectively one turn made up of 10 turns in parallel. Each of these 10 turns is the outer conductor of a "coax" braid that has been telescoped over the high-voltage insulated wire, which is to be used for the high-voltage isolation protection. The measured segments of outer conductor were strung onto the high-voltage insulated wire like beads on a necklace and "clamped" into place with shrink tubing before winding the coil. The high-voltage winding is made of commercially available, silicon-rubber insulated wire. The insulation on this wire is rated at 60 kV dc, which is probably useable to > 120 kV under pulse conditions.

Measurements of the transformer shunt inductance $L_1$ (open circuit) and leakage inductance $L_L$ (series, short circuit) performed at 100 kHz for transformer A are as follows:

$L_1$ = 2400 μh referred to 10-turn winding

$L_L$ = 2.4 μh referred to 10-turn winding

= 24.0 nh referred to 1-turn winding.

The coupling coefficient for this transformer is computed to be

$$K = 1 - \frac{L_L}{2L_1} = 0.9995 \quad .$$

The mean magnetic path length of the core is 34 cm. Since

$$L_1 = \frac{4\pi N^2 \mu A}{10^9}\ \mathrm{h} \quad ,$$

where N = number of turns, A = cross-sectional area in $cm^2$, and $\mu$ = permeability, $\mu$ can be calculated at 100 KHz for this ± 35-volt-excitation, cw-bridge measurement,

$$\mu = \frac{L_1 \times 10^9}{4\pi N^2 A} = 1700 \quad .$$

With the effective voltage V applied across the coil for t s and the cross-sectional area A given in $cm^2$, the flux density in the core $B = 10^8 Vt/NA$. If $V \simeq 2 \times 10^3$ and the flux density for this core is $B_{sat} = 4400$, the core will saturate in a time

$$t = \frac{BNA}{10^8 V} = 940\ \mathrm{ns} \quad ,$$

for a square voltage pulse. If V decreases, the time to saturation will increase.

Transformer A can charge the 100 ft of YK-198 cable (0.011 µf; 20-kV rated) to 20 kV, as well as the 0.007-µF of the barium-titanate capacitors. The spark gap can be set to break down at some voltage less than 20 kV. At a setting of 4 mm, the gap fires at about 1 µs after the firing of the x-unit. The breakdown of the spark gap places the voltage of the capacitor $C_B$ across the primary of transformer B, which in turn transforms the power to a suitable voltage and current for the bridge wire. The series inductance is considerably less than the series inductance of the x-unit plus a long cable. Transformer B is wound on a smaller core (four Ferroxcube U64 cores; cross-sectional area ≃ 14 $cm^2$) and has a lower series inductance than transformer A.

With transformer B wound with coax cable made of cathode-ray-tube wire (dc rating 30 kV), the total pulse rating for the system is at least (>120 kV)+(>60 kV) = (>180 kV). The current through the bridge wire and the voltage measured at the output terminals of transformer B are shown in Fig. 5 for $N_{BP}$ = 4 turns and $N_{BS}$ = 1 turn. It can be seen that the bridge wire fires in 280 ns and that the voltage across the output terminals of transformer B, at 2750 V, is considerably larger than the $i_1R$ voltage of 60, the remainder being the $-L\frac{di}{dt}$ contribution from the inductance of the bridge wire (~ 20 nh), its loop (~ 10 nh), and the 10-cm-length of C-cable (~ 40 nh).

Figure 6 gives the voltage and current traces for firing two bridge wires in parallel. Figure 7 gives the traces for three bridge wires in parallel. Obviously, the capacitance $C_B$ should be increased if two or three bridge wires are to be fired in parallel.

It should be noted that the circuit of Fig. 3 can reduce the firing time of the bridge wire from 600 ns to 200 ns, and at the same time give voltage isolation protection in the neighborhood of 200 kV. Also, with a 2:1 step-down for transformer B and a voltage of 3800 V, the bridge wire is fired in $t_1$ = 210 ns (see Fig. 8). One should note that the power is delivered to the bridge wire spikes as the break occurs. The time $t_1$ can be reduced even further by widening the spark gap so that $C_B$ is charged to a higher voltage, and by increasing the capacitance of $C_B$. It should be possible to fire two or three bridge wires almost as rapidly as one if $C_B$ is suitably modified.

For one bridge wire, it is clear that the reduction of $t_1$ is determined by the series inductance of the bridge wire and its connections to the transformer output terminals. For more than one bridge wire, $t_1$ is also increased by insufficient capacitance in $C_B$. The length of $t_1$ can most easily be decreased by increasing the voltage output of transformer B to perhaps 6 kV.

## III. SUMMARY OF RESULTS

By using the circuit given in Fig. 3, we have been able to reduce the time to fire an SE-1 bridge wire from 0.6μ, directly from an x-unit, to 0.21 μs, a factor of ~4.6. We expect that such a reduction in the time to fire the bridge wire of this detonator yields a significant reduction in the jitter of a complete SE-1. Also, this performance enhancement was accomplished using a 100-ft transmission line. In principle, the transmission line length is limited only by dissipative losses. Finally, the detonator bridge wires were isolated from the x-unit by a dc standoff of > 90 kV. For pulsed applications, this represents a voltage isolation of > 180 kV. Therefore, we have not only been able to achieve very high voltage isolation between the x-unit and detonator but have also significantly improved the performance of this firing system over that measured for a close-coupled bridge wire.

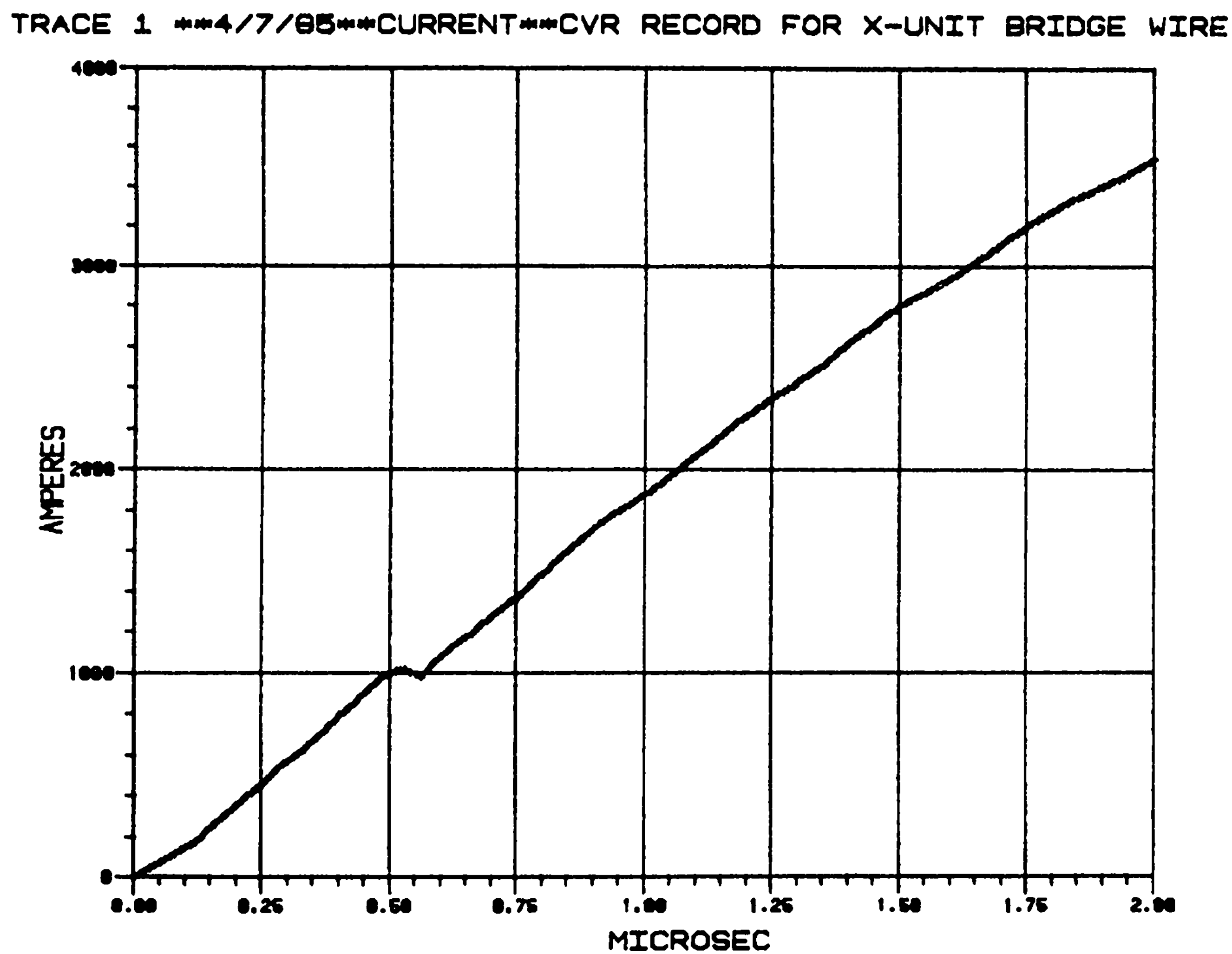



Fig. 1. Scope trace of current, i, through bridge wire connected to x-unit through 5 ft of Reynolds 167-2669C coaxial cable. 5V/div with 10:1 attenuator, 0.2 μs/div. 0.05 Ω current-viewing resistor. Current reaches $i_1$ = 50V/.05 Ω = $10^3$A at $t_1$ = 600 ns, which is time at which the bridge wire vaporizes.

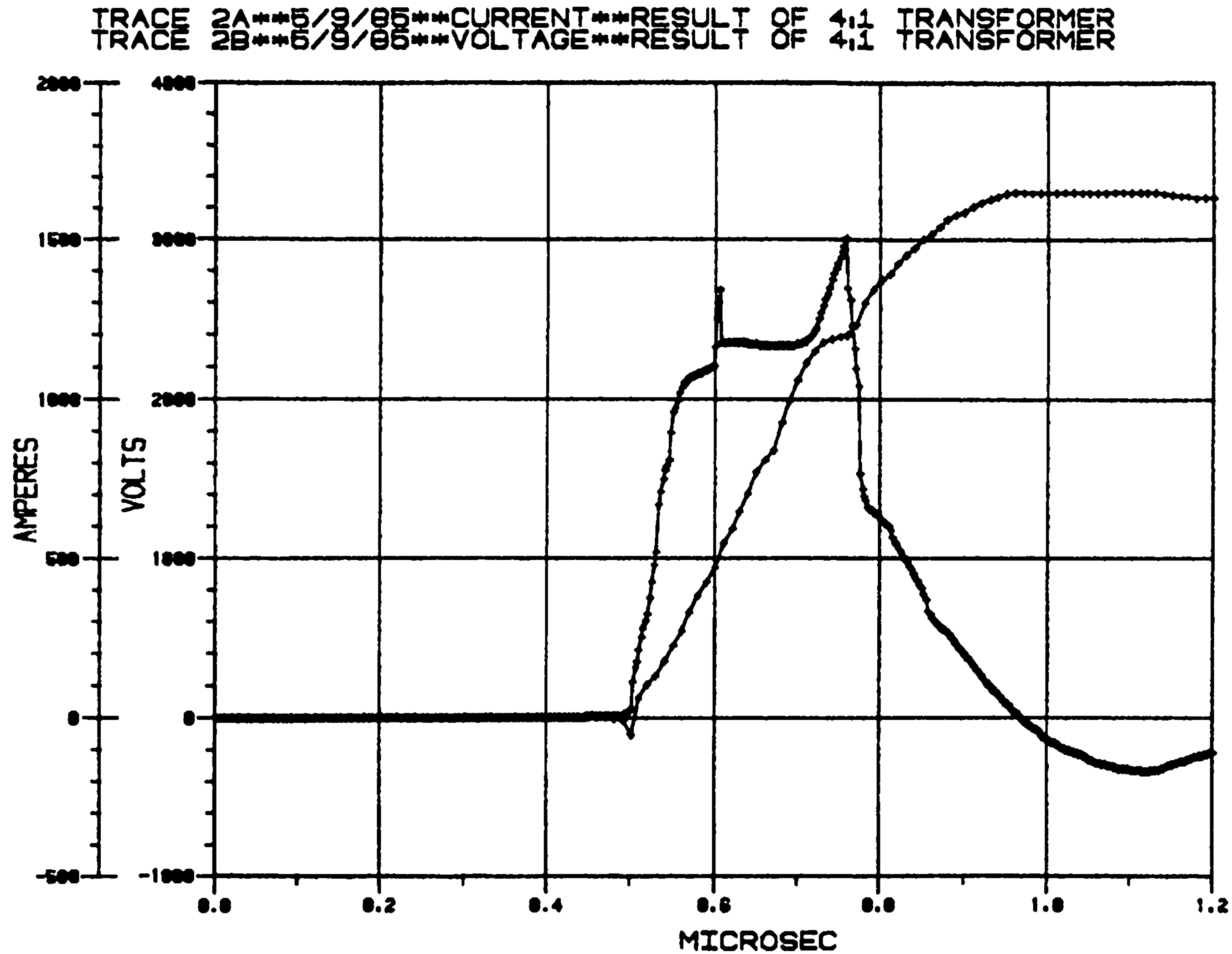



Fig. 2. Current trace, i, with circuit of Fig. 3. Transformer B has $n_{BP} = 4$, $n_{BS} = 1$. Current, i, reaches $i_1 = 60/5 \times 10^{-2} = 1.2 \times 10^3$A at $t_1 = 250$ ns. Voltage trace is at output of transformer B. The voltage rises in ~50 ns to 2400 V and remains there for 200 ns, and rises to a sharp peak of 3000 V before it descends.

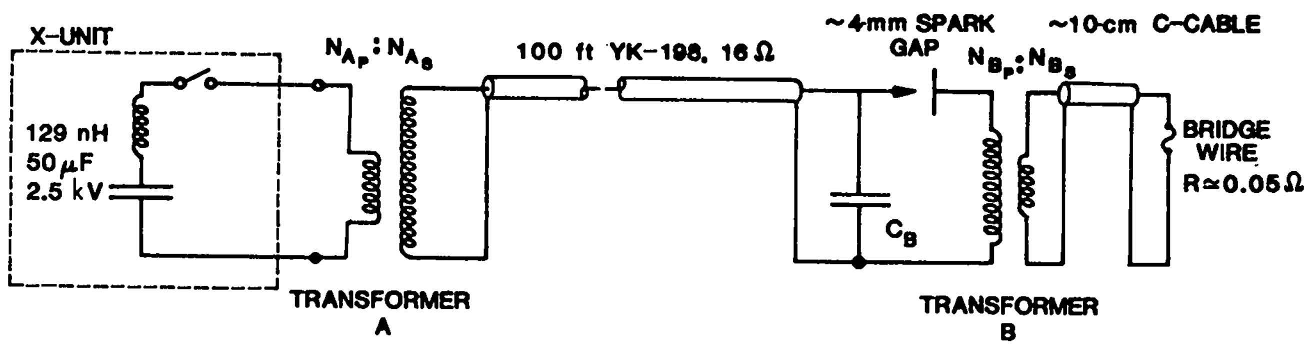



Fig. 3. Schematic of the x-unit with the transformer pulse-forming circuit.

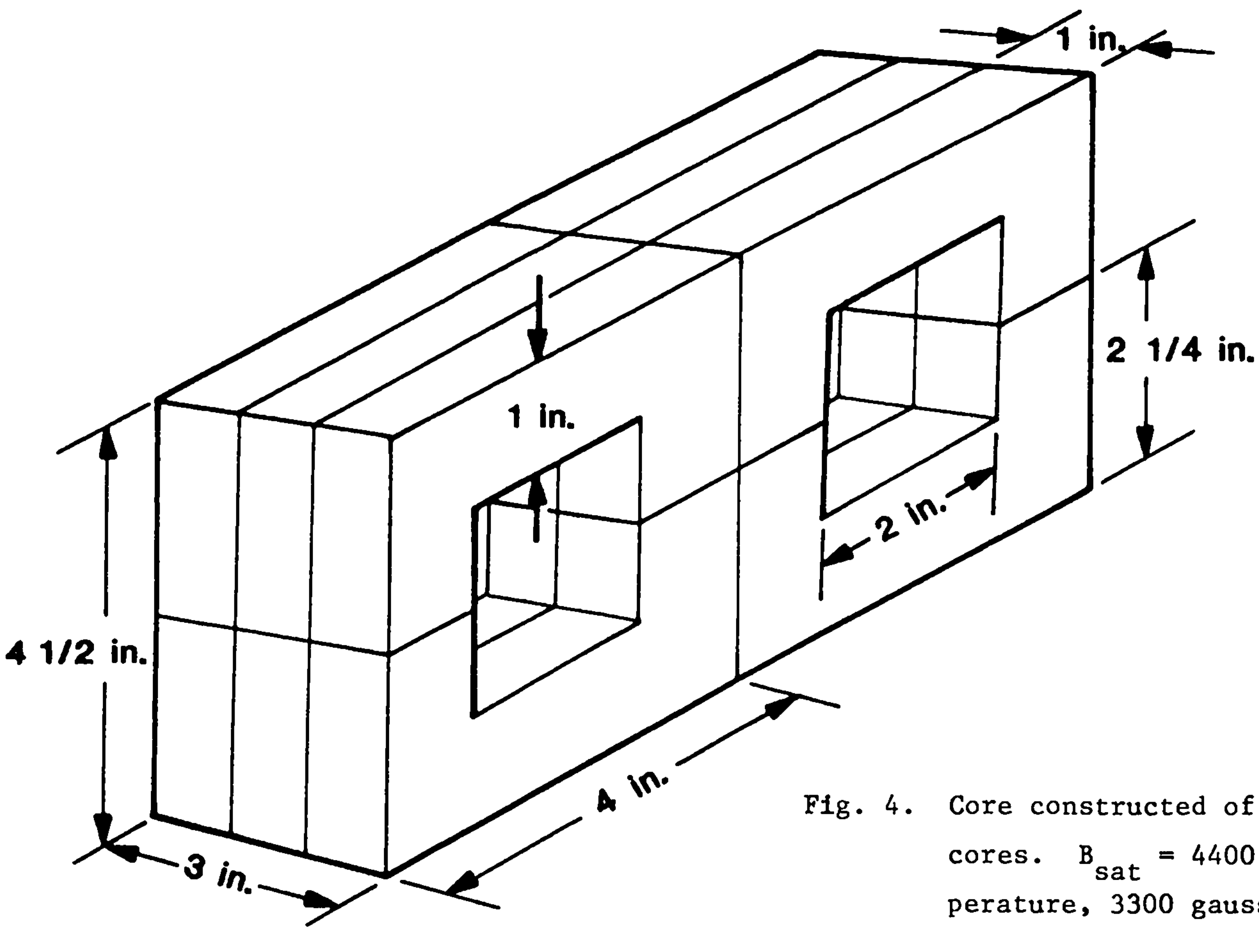



Fig. 4. Core constructed of 12 Ferroxcube "U" cores. $B_{sat}$ = 4400 gauss at room temperature, 3300 gauss at 100°C. $\mu_{initial}$ = 2700.

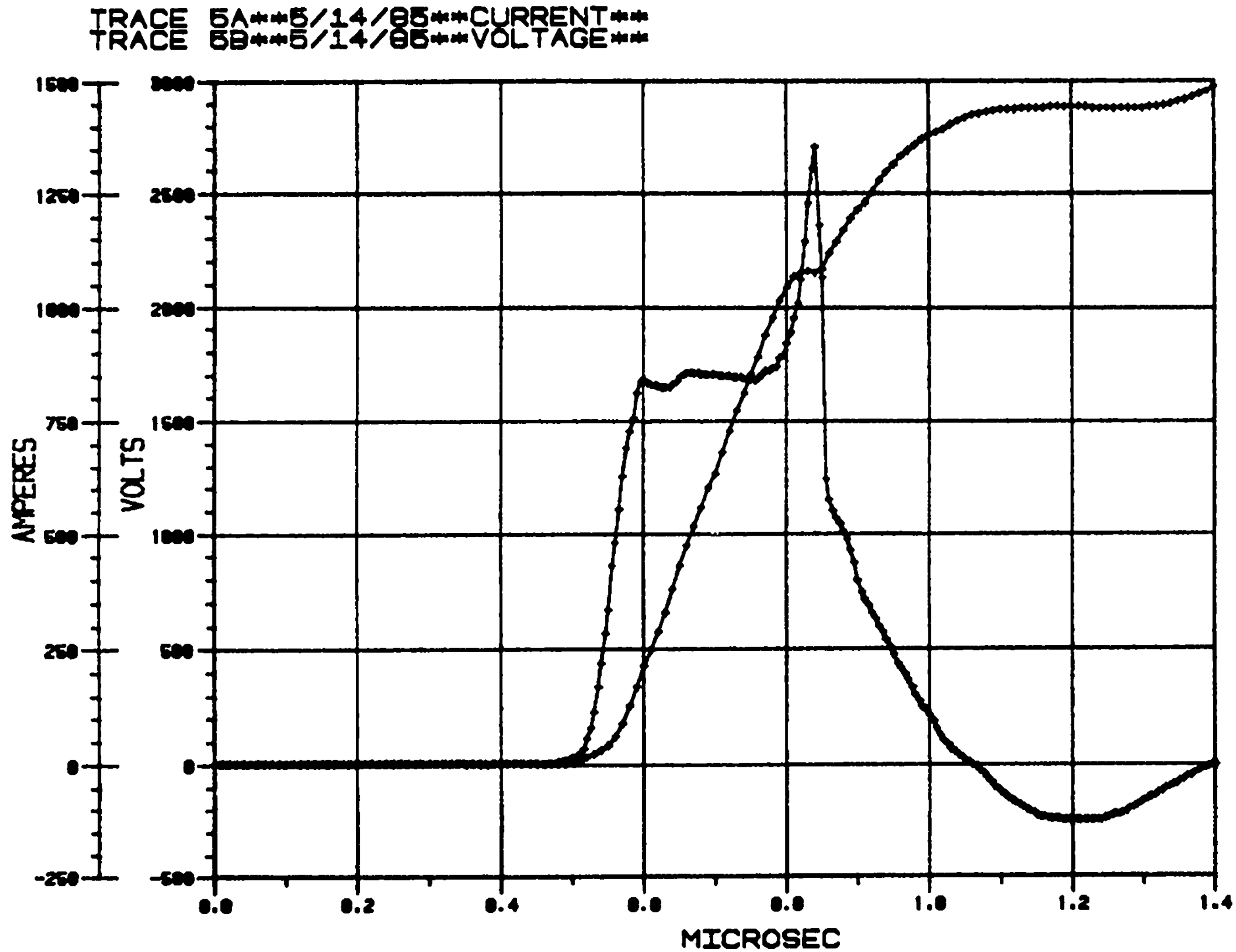



Fig. 5. Current trace is same as Fig. 2, except voltage output of x-unit was lower. Current i reaches $i_1$ = 1080 A when the wire turns to vapor at $t_1$ = 280 ns. Voltage trace rises in 100 ns to 1750 V, remains there for 200 ns, and rises sharply to a peak of 2750 V in 280 ns from the start of action.

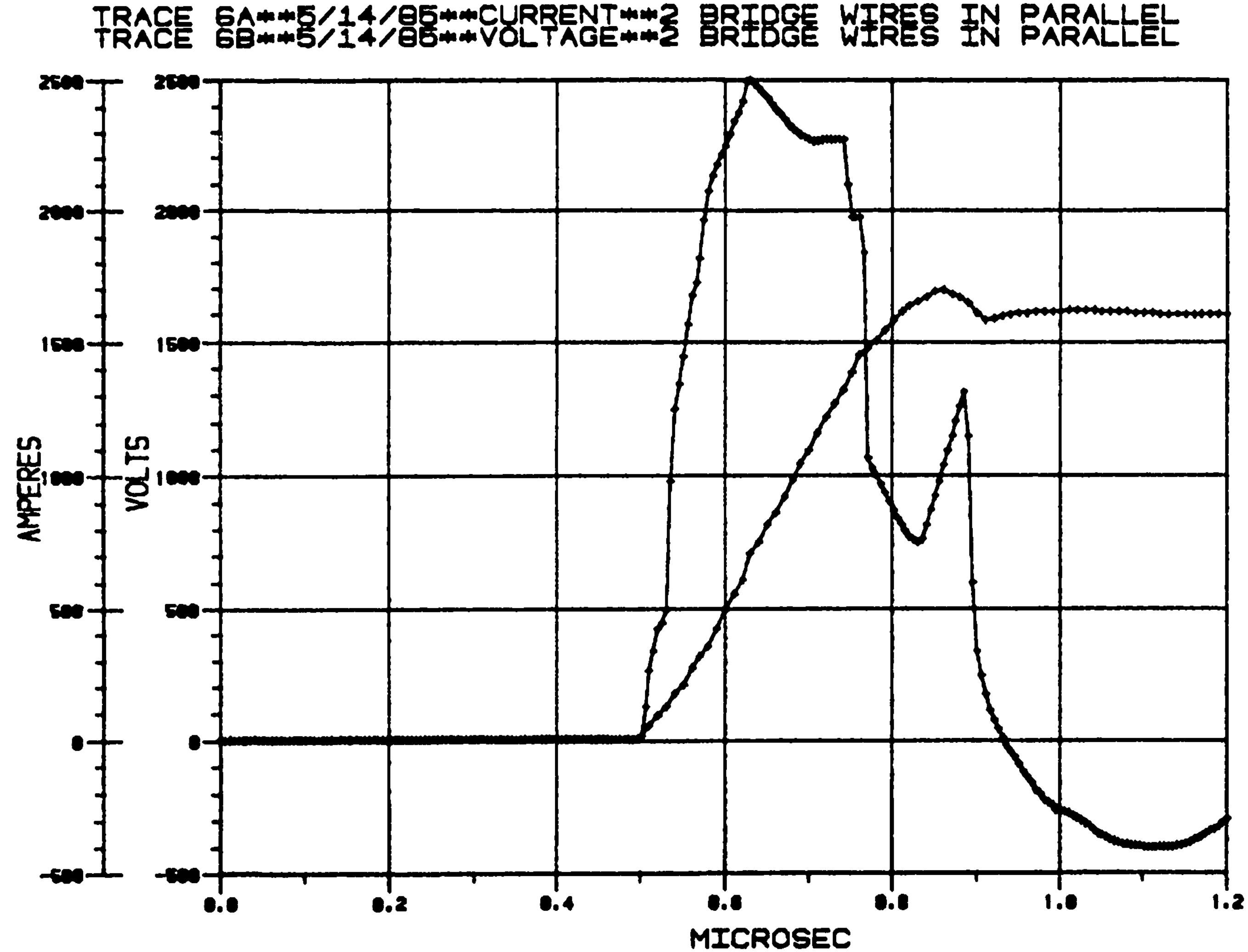



Fig. 6. Current trace is same as Fig. 2, except that two bridge wires are being fired in parallel. Total current reaches $i_1$ = 1700 A in al ≅350 ns. Voltage trace rises to 2500 V, decreases to $\sim$800 V, and spikes to 1300 V at $t_1$ = 390 ns.

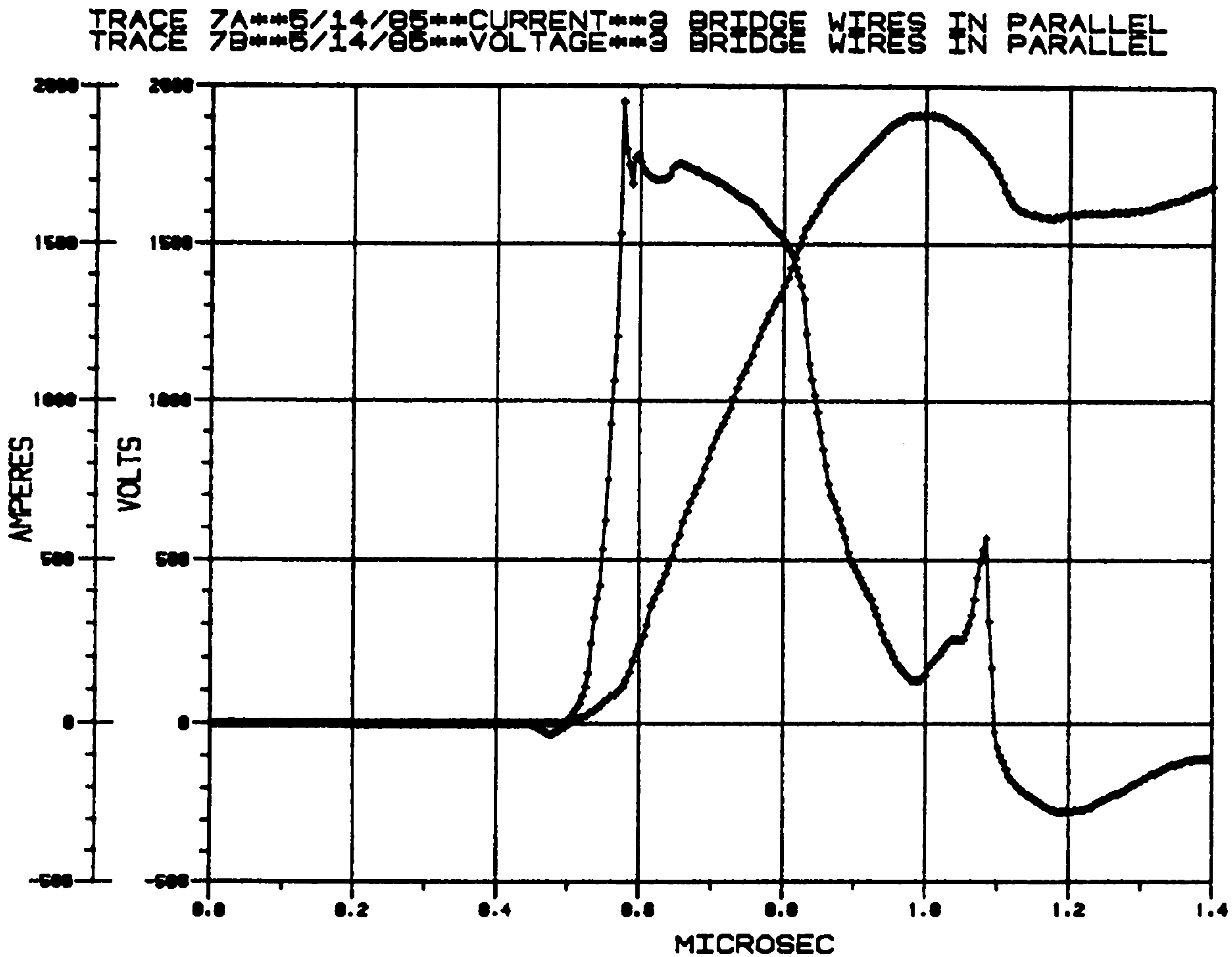



Fig. 7. Current trace is same as Fig. 6, except that three bridge wires are fired in parallel. Maximum current reaches 1900 A. Voltage trace rises to 1700 V and decreases to ∿130 V at the time of the sharp peak of ≤ 550 V, which signifies the vaporization of the wire, and sets $t_1$ at 580 ns.

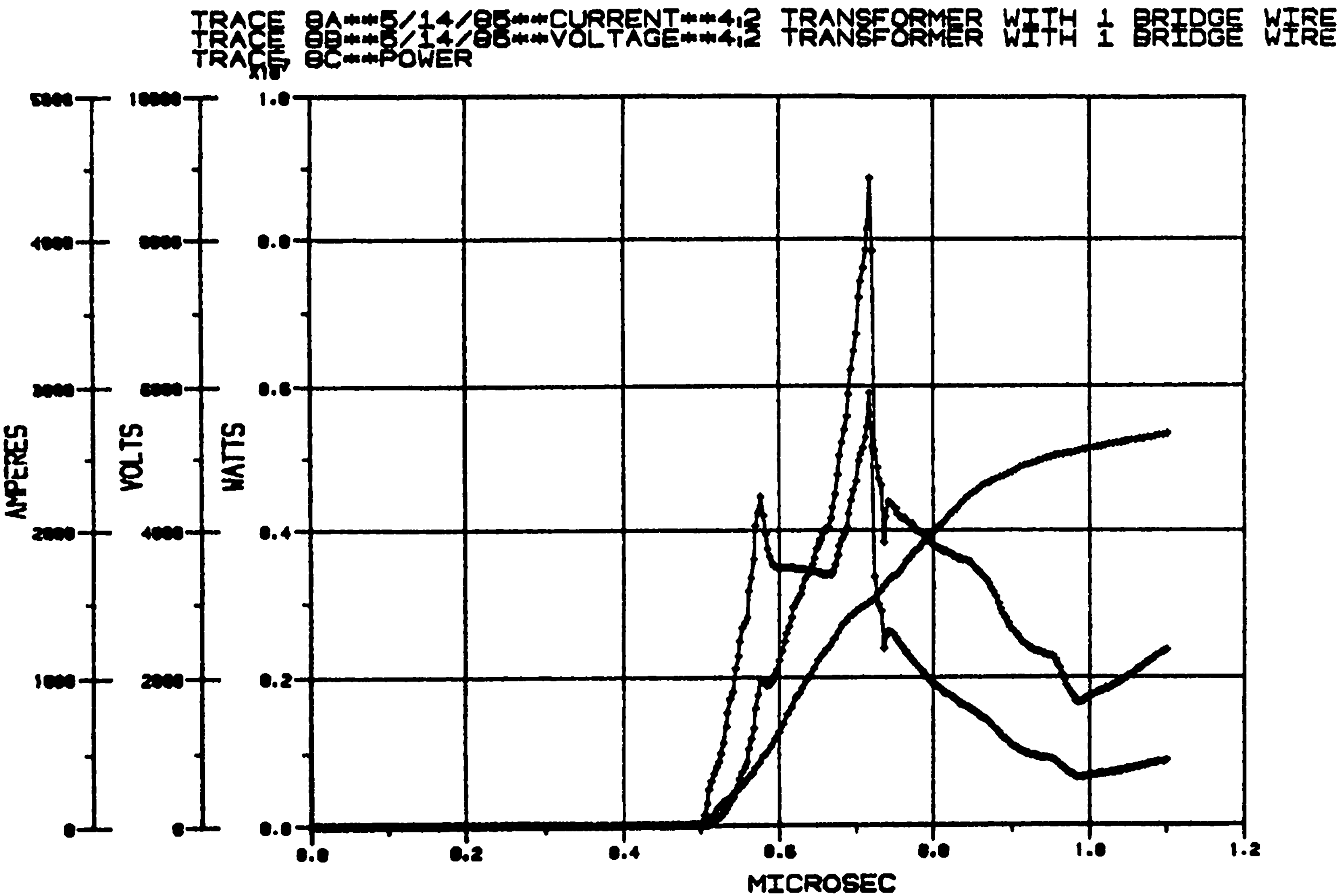


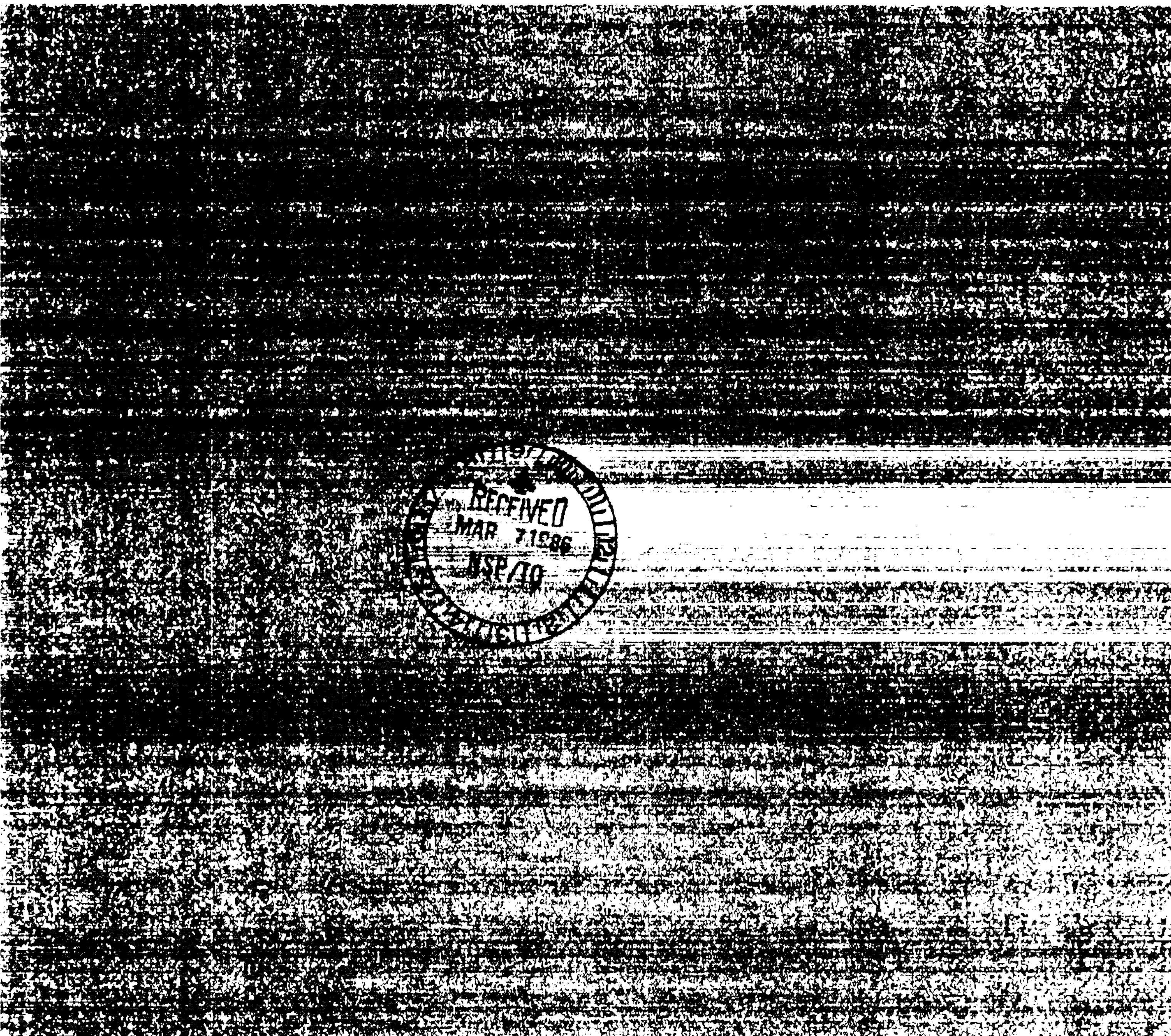

Fig. 8. Current trace with one bridge wire and for transformer B $n_{BP} = 4$ and $n_{BS} = 2$ (a 2:1 voltage step-down). The current $i_1 = 1500$ A is reached at $t_1 = 210$ ns. Voltage trace rises to 4200 V and decreases to 3600 V when the sharp peak to 6000 V indicates the vaporization of the wire and sets $t_1$ at $t_1 = 210$ ns. Power trace is simply the voltage multiplied by the current. Note that this quantity peaks at 890 MW when the bridge wire is destroyed.

Printed in the United States of America
Available from
National Technical Information Service
US Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Microfiche (A01)

| Page Range | NTIS Price Code | Page Range | NTIS Price Code | Page Range | NTIS Price Code | Page Range | NTIS Price Code |
|---|---|---|---|---|---|---|---|
| 001-025 | A02 | 151-175 | A08 | 301-325 | A14 | 451-475 | A20 |
| 026-050 | A03 | 176-200 | A09 | 326-350 | A15 | 476-500 | A21 |
| 051-075 | A04 | 201-225 | A10 | 351-375 | A16 | 501-525 | A22 |
| 076-100 | A05 | 226-250 | A11 | 376-400 | A17 | 526-550 | A23 |
| 101-125 | A06 | 251-275 | A12 | 401-425 | A18 | 551-575 | A24 |
| 126-150 | A07 | 276-300 | A13 | 426-450 | A19 | 576-600 | A25 |
| | | | | | | 601-up* | A99 |

*Contact NTIS for a price quote.





Los Alamos