

FAST PULSER FOR HIGH-ALTITUDE IGNITION RESEARCH

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*Abstract*¹

A jet engine can flame out at high altitude because the igniter cannot couple enough energy into the low-pressure air-fuel mixture. To reignite the engine, the aircraft must descend to a lower altitude where the air pressure is higher.

Under a recent U.S. Air Force SBIR grant, Diversified Technologies, Inc. designed and built a fast ignition pulser. The pulser was delivered to the Air Force Research Laboratory for testing to determine the optimum parameters for high-altitude jet ignition.

The pulser, based on magnetic pulse compression, is immune to arcs at the output. It delivers a pulse at 27 kV and 37 mJ with a rise-time of 17 ns at a pulse rate of 8 kHz. The overall efficiency is 38%. This paper discusses the design and performance of the laboratory pulser.

I. DESIGN

A. *Pulser Design*

The pulser design is based on the following considerations:

- Ignition is produced by free electrons and excited atoms in the air-fuel mixture. Because the electrons and excited atoms recombine rapidly, A high pulse rate should produce better ignition².
- A voltage between 20 and 30 kV is optimum. Below 20 kV, air breakdown is unreliable; above 30 kV, the required insulation is increasingly demanding.
- The energy per pulse should be small to minimize the power that the pulser needs to deliver. This pulse energy is determined by the capacitance of the coaxial cable between the pulser and the spark plug. In the design here the three foot long cable has a capacitance of about 100 pF, giving a pulse energy of 37 mJ at 27 kV.
- A fast pulse risetime produces a higher voltage before the gas breaks down, coupling more energy into the discharge. For this design the risetime was specified to be less than 25 ns.
- Finally, the pulser should be able to operate directly into the load when the load shorts. Eliminating the series-protection resistor or capacitor maximizes the energy coupled into the discharge.

To meet these requirements we designed, built, and tested the magnetic-compression pulser shown in Figure 1. The laboratory pulser can operate directly into a short. It has the following characteristics:



Figure 1. Fast ignition laboratory pulser delivered to the Air Force Research Laboratory.

- 15 to 30 kV output voltage
- 17 ns risetime from 5 to 25 kV
- 0 to 8 kHz pulse rate

B. *Design Equations*

There are two basic equations needed to design a conventional magnetic pulse compression circuit. During the input pulse, the saturable inductor needs to hold off the applied sinusoidal voltage:

$$\int V dt = 0.5 V_{peak} t_{charge} = N A \Delta B \quad (1)$$

where V is the voltage across the saturable inductor, t_{charge} is the charging time, N is the number of turns on the core, A is the cross-sectional area of the core, and ΔB is the flux swing in the core, which is typically twice the saturated magnetic field strength.

Writing this in terms of the charge time,

$$t_{charge} = \frac{2 N A \Delta B}{V_{peak}} \quad (2)$$

The second equation is the duration of the output half sine wave pulse:

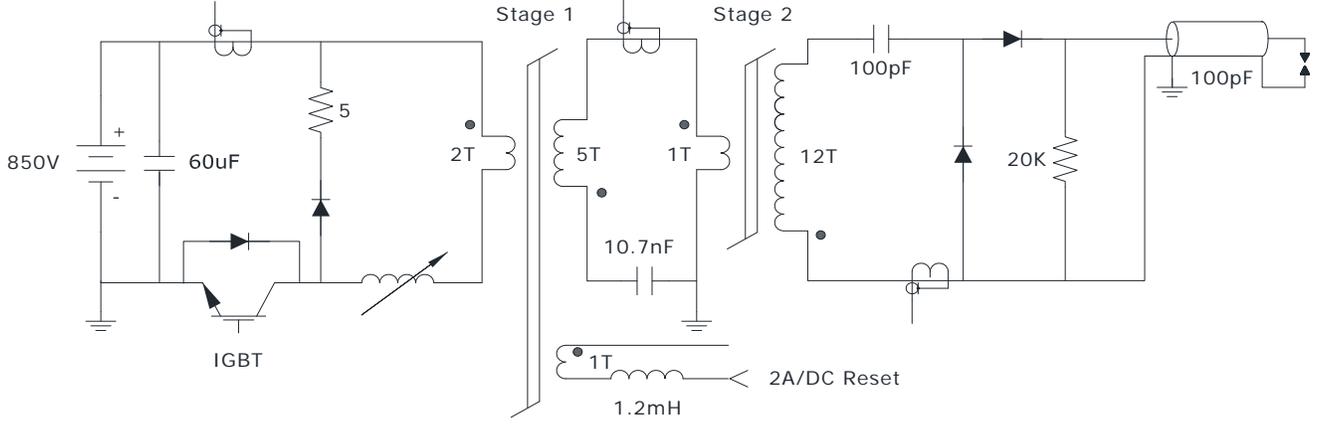


Figure 2. Simplified circuit diagram of the fast-ignition pulser; there are two transformer-compression stages.

$$t_{\text{discharge}} = \pi \sqrt{L_{\text{total}} C_{\text{total}}} \quad (3)$$

$$\approx \pi \left[\frac{\mu_0 N^2 A}{l} \frac{C_0}{2} \right]^{0.5} \quad (4)$$

where μ_0 is the permeability of free space, l is the average circumference of the core, and C_0 is the capacitance per stage. In this equation, we assume that the load is a capacitor with a capacitance equal to the upstream capacitance; this gives an effective capacitance that is half that of a single capacitor. The approximation assumes that the saturated permeability of the core is given by the permeability of free space, and that the inductance of the wound core is much larger than the stray inductance outside of the core. Note, however, that the stray inductance becomes increasingly important as the discharge time becomes faster.

The design of a magnetic pulse compression system also depends on the losses; these are particularly significant for the low pulse energy in this design.

C. Magnetic Pulse Compression Circuit

A simplified circuit diagram of the pulser is shown in Figure 2. The pulser has an initial IGBT switch and two transformer-pulse compression stages. We describe circuit operation beginning at right hand, output end.

The second stage was designed to produce a rise-time of less than 25 ns on the 100 pF output cable. The 100 pF storage capacitor is charged to 30 kV by the 12-turn secondary winding through the (vertical) diode string. When the core saturates, the storage capacitor is grounded through the saturated secondary inductance. The charging diode string is back-biased, and the transmission line is then resonantly charged through the (horizontal) series diode string. The series diode string isolates the load from

subsequent transients in the second pulse-compression stage.

The single-turn primary of the second-stage transformer was made of a short length of 1.125" diameter copper pipe, offset toward the grounded end of the 12-turn secondary winding to reduce the voltage stress. The 100 pF storage capacitor on the secondary is an equivalent capacitance of $100 \text{ pF} \times 12^2 = 14.4 \text{ nF}$ on the primary when the transformer core is unsaturated. The stage 2 transformer is reset during the charge of the 10.7 nF first-stage capacitor.

The first stage was designed to deliver a 150 ns pulse of current to the single-turn second-stage primary. This time is short enough so that the 100 pF storage capacitor is fully charged before the second core saturates. The first stage capacitor is made of two parallel strings of three series 16 nF mica transmitting capacitors. Typically the 10.7 nF capacitor assembly is charged by the first stage transformer to 3.8 kV in 800 ns.

The first stage transformer supports 310 V- μs per turn. The 5-turn stage 1 winding contributed a substantial amount of saturated inductance to the stage 2 primary circuit, which drove up the required voltage on the 10.7 nF capacitor.

We can vary the output voltage by adjusting the DC input voltage; this also affects the first-stage charging time. The IGBT is turned off just as the primary core saturates. The leakage inductance associated with the first-stage windings combined with the 67 nF apparent series capacitance on the primary side gives a charge time of 800 ns for full-voltage operation. As the DC voltage is lowered to reduce the output voltage, the saturation time of the first stage increases. We slightly increase the series inductance and lengthen the IGBT charge time to achieve 180° conduction.

Shortly after the first stage saturates and delivers its 150 ns pulse to the second stage, the negative residual voltage on the 10.7 nF capacitor drives the stage 1 core

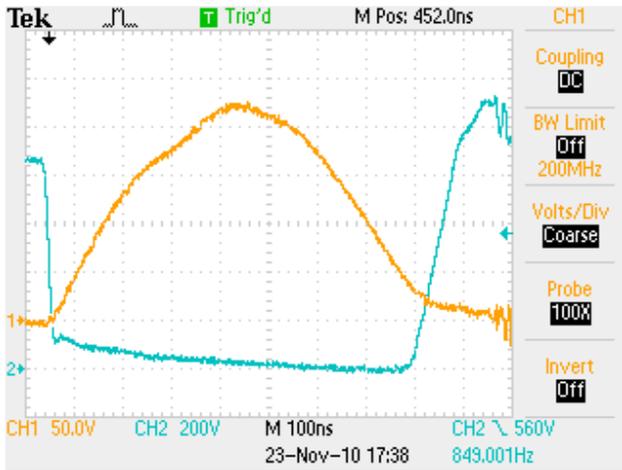


Figure 3. Voltage and current in the initial IGBT. (Trace 2) Voltage across the IGBT, 200 V/div. (Trace 1) Current through the IGBT, 50 A/div. Time scale 100 ns/div.

into reset, inducing a substantial negative voltage on the two-turn primary. This causes the IGBT forward voltage to rise substantially above the power supply voltage. A power diode and 5 Ω series resistor control this reset transient, keeping the IGBT forward voltage below its rated 1200 V.

Interestingly, stage 1 reset is nearly independent of the direct reset current and associated inductance.

II. OPERATIONAL WAVEFORMS

The following waveforms describe the operation of the pulser. All these traces were taken without a spark-gap load and with the power supply at 850 V.

Figure 3 shows the voltage and current in the initial IGBT. The initial charging pulse is 800 ns long. The peak current is 225 A, so the charge transferred is

$$Q = It = 2/\pi \times 225 \text{ A} \times 800 \text{ ns} = 115 \text{ } \mu\text{C}.$$

This drops the voltage on the 60 μF input capacitor by only 2 V.

The energy carried by this charge is

$$E = QV = 115 \text{ } \mu\text{C} \times 850 \text{ V} = 98 \text{ mJ}.$$

Figure 4 shows the currents in the first and second capacitors. The charging pulse on the second capacitor is 140 ns long, a factor of 5.7 times shorter than the initial 800 ns pulse.

The turns ratio on the transformer is 2:5, so the current in the secondary would ideally be 2.5 times less than in the 225 A in the primary, or 90 A. Instead, the peak current during charge of the first capacitor is about 80 A.

With the measured current, the expected voltage on the first capacitor is

$$V = It / C = 2/\pi \times 80 \text{ A} \times 800 \text{ ns} / 10.7 \text{ nF} = 3.8 \text{ kV}.$$

The actual voltage (not shown) on the first capacitor is 3.7 kV. At this voltage, the energy stored in the first capacitor is

$$E = 0.5 C V^2 = 0.5 \times 10.7 \text{ nF} \times (3.7 \text{ kV})^2 = 73 \text{ mJ}.$$

This is a nominal energy transfer efficiency of 75% (73 mJ / 98 mJ).

Figure 5 shows the output voltage, along with the currents in the first and second capacitors. The output voltage has a peak of 27 kV; it rises from 5 kV to 25 kV in 17 ns. Note that the output voltage is at 3 kV before it rises to its peak value.

The peak discharge current in the first capacitor is 440 A. For the 1:12 step-up ratio in the second transformer, the expected charge current in the second capacitor would be 37 A. The measured current from the trace is about 40 A.

Integrating the charging current in the second capacitor gives a charge of approximately 3.7 μC, which in turn gives a calculated voltage of 37 kV, much more than the 27 kV measured. This difference is due to energy loss in the magnetic pulse compression. The energy stored in the output cable is

$$E = 0.5 \times 100 \text{ pF} \times (27 \text{ kV})^2 = 37 \text{ mJ}.$$

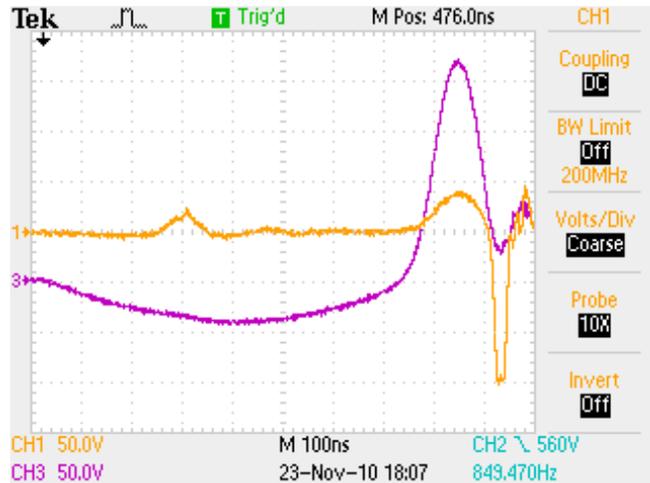


Figure 4. Currents in the first and second capacitors. (Trace 3) Current in the first capacitor, 100 A/div. (The monitor has a 50 Ω terminator, halving the output.) (Trace 1) Current in the second capacitor, 50 A/div. Time scale 100 ns/div

This is a nominal energy transfer of 51% (37 mJ / 73 mJ) in the second stage, and an overall energy transfer of 38% (37 mJ / 98 mJ). The operational efficiency is somewhat larger than this, since some of the energy is reflected back into the initial charging capacitor.

III. CONCLUSIONS

The pulser we developed produces an output of 28 kV, 17 ns risetime, 36 mJ pulse, 8 kHz pulse rate. The pulser is based on magnetic compression, and so can operate into a short circuit without damage. A pulser with this high a pulse rate has not been previously available for ignition testing, to the best of our knowledge.

IV. ACKNOWLEDGEMENTS

We particularly appreciate the support of Dr. Biswa Ganguly of the Air Force Research Laboratory.

V. FOOTNOTES

¹ Work supported by the U.S. Air Force under an SBIR grant

² Suggested by Dr. Biswa Ganguly, Air Force Research Laboratory, Dayton, OH, private communication

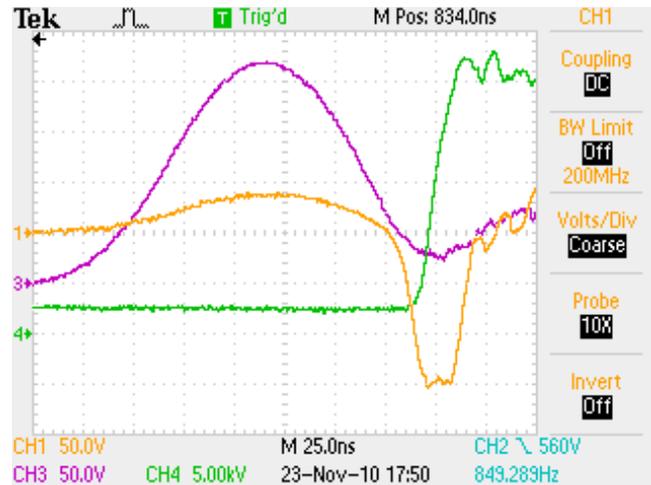


Figure 5. Output voltage and capacitor currents.
 (Trace 4) Output voltage, 5 kV/div.
 (Trace 3) Discharge current in the first capacitor, 100 A/div.
 (Trace 1) Current in the second capacitor, 50 A/div.
 Time scale 25 ns/div.