SENSITIVITY OF IGNITRONS TO STRAY CAPACITANCE

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The surprising sensitivity of ignitors was encountered on RACE, a compact torus device. Its capacitor bank has both the common reverse-crowbar circuit and an unusual forward-crowbar circuit that made this investigation necessary. The ignitors were fired with high-capacitance coaxial-cable pulse transformers. When the bank fired, because of negative bank charge, forward-crowbar ignitrons saw both positive anode voltage and a positive pulse to their ignitors coupled through pulse transformer capacitance. One tube prefired as low as 3 kV. Prefires ceased when coaxial transformers were replaced with double-shielded transformers. Pulse duration and energy were much less than expected. The computed ignitor pulse RC time was only 5.6 ns, far less than a typical 250-ns anode firing delay. The positive capacitive energy input to the ignitor was 0.14 mJ, more than 3 orders of magnitude less than the ignitron firing chassis.

Introduction

The usual triggering problem of ignitrons is getting enough power into low-resistance ignitors. The problem of ignitors that are too sensitive is unusual. This problem was encountered in a capacitor bank circuit for the Ring ACcelerator Experiment (RACE), a compact torus device. In addition to the common reverse-crowbar circuit, RACE also has an unusual forward-crowbar circuit, which is fired before voltage reversal to decrease faster the current through resistors in series with the load.

The ignitor, after which the ignitron is named, is the trigger electrode. (See Figure 1.) The upper shank is graphite and is supported by a rod from the ignitor feedthrough bushing. The lower end consists of a sintered mixture of carbon, silicon, and boron. The tip is ground to a diameter of a few millimeters and is immersed into the mercury pool cathode. Normally, mercury does not wet the ignitor and forms a convex meniscus. As a result, the resistance between the ignitor and the mercury pool ranges from about 50 to 250 ohms.

In pulsed power applications, the tube is fired by pulsing the ignitor with a positive voltage, generally 1 to 4 kV. Arc spots form where the mercury meniscus contacts the ignitor tip. Very quickly, a discharge forms between the mercury pool and the ignitor support, bypassing the ignitor-cathode interface. If the anode voltage is positive with respect to the cathode, a discharge also forms between the cathode and the anode.

In many pulsed power applications, especially with high current reversal, metal is evaporated from arc spots on the ignitron stainless steel wall or on a metal anode. This vapor plates the ignitor, or the ignitor feedthrough bushing, allowing mercury to wet those surfaces, sometimes forming a concave meniscus. This coating shunts energy from the trigger circuit and is perhaps the most common failure mode.

This application was unusual in that the ignitors were too sensitive for the circuit as originally designed.

Bank Performance

The bank has 18 ignitrons: 6 start tubes, 6 reverse-crowbar tubes, and 6 forward-crowbar tubes. (See Figure 2.) These tubes were selected from a large number used in another system, so that tube conditions varied greatly. (See Table I.) Initially, two start tubes prefired and had to be replaced. Consequently, when tubes in the forward-crowbar circuit prefired at 3 kV, weak tubes were blamed. Two were replaced, although they held 30 kV on hipot tests. Tubes Nos. 2 and 3 still prefired at 3 kV, and No. 4 prefired once at 3.5 kV, so another explanation was sought.

The ignitron firing chassis was turned off, but the problem persisted. Then the cables to the ignitor pulse transformers were disconnected. This raised the prefire level to 3.5 kV, and only Tube No. 2 prefired, although No. 6 prefired at 4 kV. With additional tests, Ignitor 2A was identified as the most sensitive one. Table I shows the ignitor-to-cathode resistance measurements.

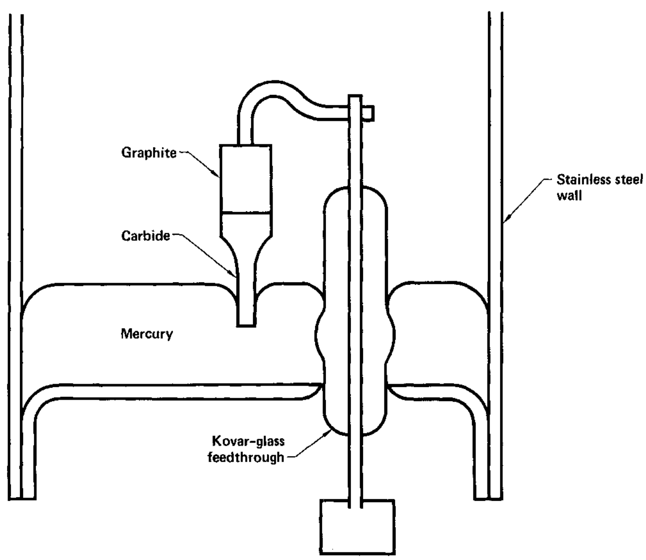

Figure 1. Cross section of ignitron mercury pool cathode and ignitor.

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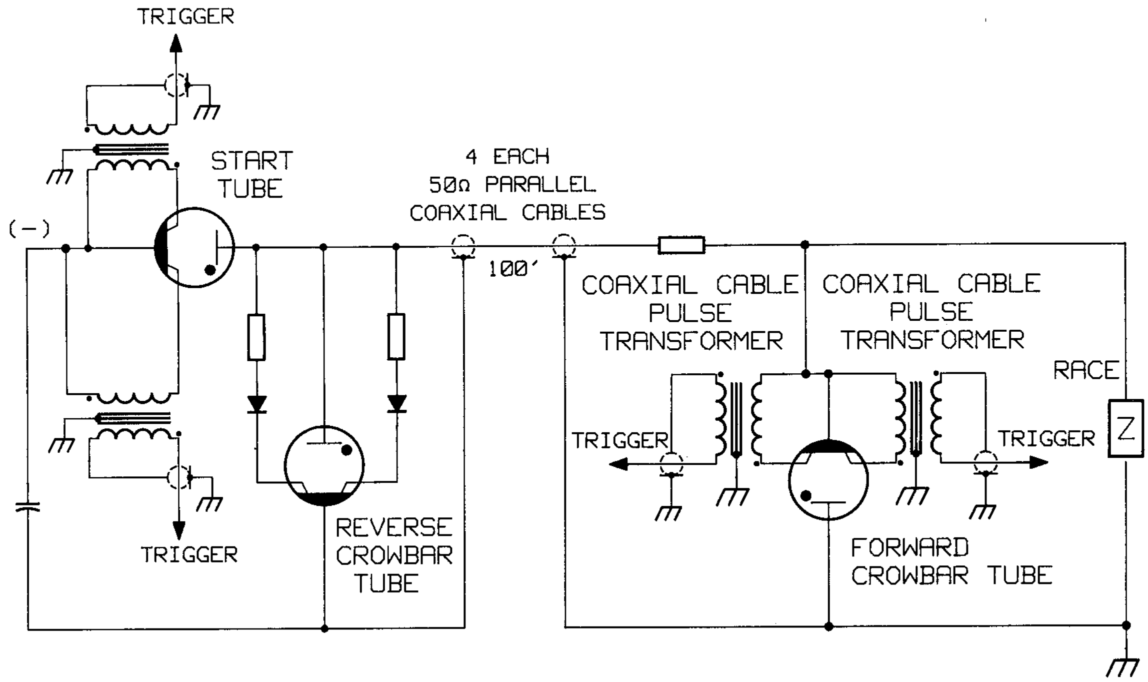

Figure 2. Simplified diagram of capacitor bank circuit. This is one of six parallel sections.

The bank was built with a pulse transformer on each of two ignitors of tubes in the forward-crowbar circuit. These were wound with coaxial cable using the braid as the primary and the center conductor as the secondary. (See Figure 3.) Hundreds of these transformers have been used successfully for many years at Lawrence Livermore National Laboratory and other laboratories. However, in this case, the high interwinding capacitance of the coaxial cable caused some ignitors in the forward crowbar to prefire.

The unusual combination of two conditions led to discovering the sensitivity of the ignitors to transformer capacitance:

1. The forward-crowbar circuit, in which there was forward voltage on the tubes as soon as the start tubes were fired. The tubes were therefore able to fire if the ignitors were pulsed. This is not the case in the familiar reverse-crowbar circuit.

2. A negatively charged bank that made the cathodes of the forward-crowbar tubes go from ground potential to the bank charge voltage when the start tubes were fired. The pulse transformer secondary was tied to the cathode, and the primary was tied to ground. This put a large positive pulse on the ground side of the pulse transformers. This pulse couples to the ignitor through the interwinding capacitance of the pulse transformers. Thus, conditions were right for unwanted triggering.

The capacitance of the pulse transformer secondary to the grounded primary is 431 pF, the capacitance of the 14.3 ft of

Table I. Ignitor resistance in the RACE gun bank tubes.

Tube	Ignitors	(Ohms)	Comments
1	1A	69	No prefires.
	1B	9	
2	2A	134	Prefired at 3 kV with grounded firing
	2B	17	cables. At 3.5 kV without cables.
3	3A	40	Prefired at 3 kV with grounded firing
	3B	19	cables. No prefires without cables.
4	4A	28	Prefired once at 3.5 kV with grounded
	4B	111	firing cables.
5	5A	102	No prefires.
	5B	161	
6	6A	241	Prefired once at 4 kV without
	6B	408	grounded firing cables.

50-ohm coaxial cable with which it is wound. With the grounded trigger cable removed, the capacitance drops to 106 pF; the cable capacitance is then in series with the capacitance of the shield to the iron core and frame, which is 142 pF.

To confirm our explanation, Ignitor 2A was grounded through a 222-pF capacitor. Tube No. 2 prefired at 3.5 kV. Then a handy 5.5-ft piece of 50-ohm coaxial cable was tied to Ignitor 2A and the braid was grounded. The capacitance was 165 pF. Again Tube No. 2 prefired at 3.5 kV.

When the coaxial-cable pulse transformers on the forward-crowbar tubes were replaced with double-shielded transformers that had 0.03 pF interwinding capacitance, the problem ceased. (See Figure 4.) Firing two ignitors per tube was a conservative luxury originally permitted by the availability of both pulse transformers and 16-output ignitron firing chassis. However, only enough of the new double-shielded transformers were hand-made to fire one ignitor per tube.

Discussion

There were three surprises in this series of tests:

The first surprise was that there had been a capacitance problem latent in our coaxial pulse transformers for many years, just waiting for the right circuit in which to cause problems.

The second surprise was that such a short pulse could trigger a tube. The performance of the pulse transformer with the trigger cable disconnected was computed using the equivalent circuit shown in Figure 5. With the ignitor resistance of 134 ohms and the distributed transformer capacitance to ground of 142 pF, the RC time constant was only 5.6 ns. After 22 ns, the voltage from the cathode end of the transformer cable arrives at the other end, causing the voltage to go negative on the ignitor. After this time no additional energy would be expected to go into forming arc spots. By then arc spots would have formed, and their further multiplication would be driven by anode voltage. Either time is far less than a typical 250-ns anode firing delay.

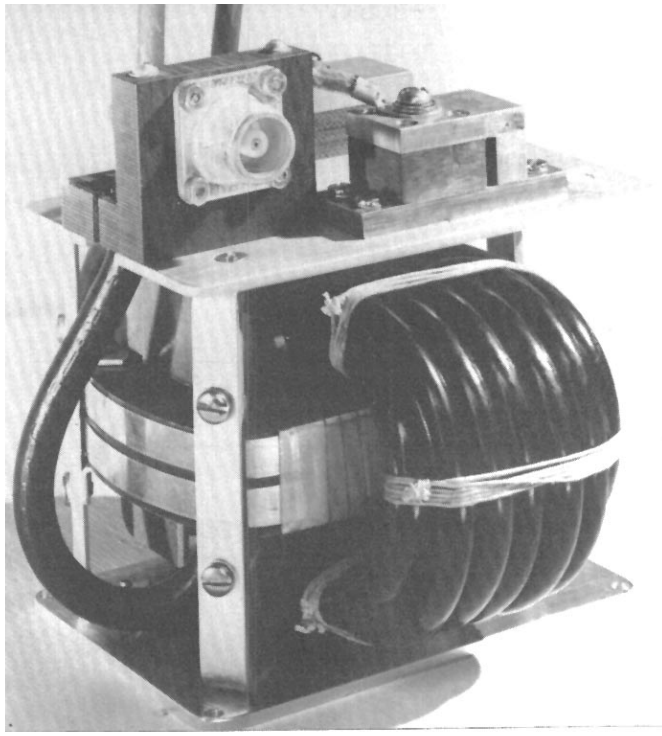

Figure 3. Coaxial-cable pulse transformer.

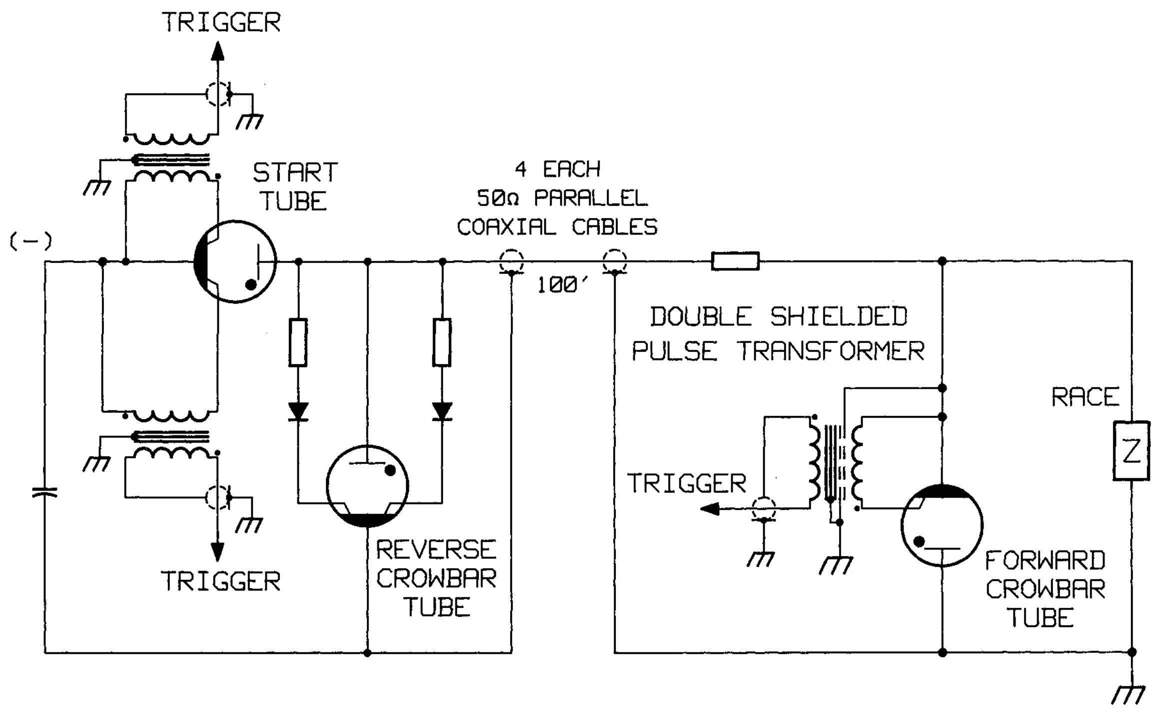

Figure 4. Simplified diagram of capacitor bank circuit, with double-shielded pulse transformer on the forward crowbar. This is one of six parallel sections.

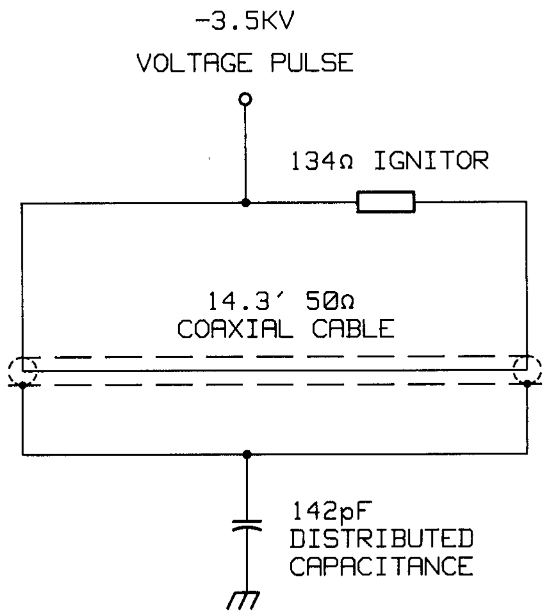

Figure 5. Equivalent circuit for coaxial-cable pulse transformer with trigger cable disconnected.

We may look at shortened pulse duration as a symptom of energy diversion from the normal ignitor interface into a parallel resistive path. Therefore, it should be expected that the highest-resistance ignitors would be the most sensitive. However, ignitor resistances in Tube No. 6 were the highest of all (241 and 408 ohms), yet it was less sensitive than Tube No. 2. Also, Tube No. 5 had one ignitor with a higher resistance (161 ohms) than Tube No. 2 (134 ohms), yet it did not prefire at all. In addition, Tube No. 3 prefired when the grounded firing cables were connected, in spite of the fact that its highest ignitor resistance (40 ohms) was the lowest of the six tubes. However, it did not prefire when the firing cables were removed. Probably these variations from the expected trend reflect the number of variables in the manufacture and previous usage of the tubes. Unfortunately, in our busy experimental program there was no time to survey the prefire sensitivity of each tube.

The third surprise was that so little capacitive energy was required to cause prefires. At 3.5 kV, the energy delivered to the ignitor, before polarity reversal, was only 0.14 mJ, assuming constant 134-ohm resistance. However, it would be expected that a discharge would short out the resistance of the interface before the full positive energy was delivered. Therefore, the real energy to fire the tube would be somewhat less than the calculated value. This energy is more than 3 orders of magnitude less than the 0.45 J stored at 3 kV in the 0.1 μF capacitor of the ignitron firing chassis, which is considered sufficient for firing tubes, even after long usage has reduced their ignitor resistances.

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