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A High Voltage Pulse Generator for the Mod-Anode of the Cluster Klystron

Yongxiang Zhao and Hai-peng Wang
Brookhaven National Laboratory
Upton, NY 11973

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CENTER FOR ACCELERATOR PHYSICS

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A HIGH VOLTAGE PULSE GENERATOR FOR THE MOD-ANODE OF THE CLUSTER KLYSTRON

Yongxiang Zhao, Hai-peng Wang

Physics Department
Brookhaven National Laboratory
Upton, NY 11973

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Abstracts

A high voltage pulse generator using Zarem type was developed. The advantage of the Zarem type circuit is that it does not require a matched load. In our case the pulser is dedicated to drive a mod-anode, which is a capacitive load. Therefore the Zarem type circuit is desirable.

This report addresses systematically the R & D work, including the basic principle and the designing consideration, the low voltage and high voltage experiments. A lot of irregular phenomena were observed, including ringing, pulse "skirt" and "deficiency". Also addressed are the analyses, simulation and solutions.

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1. INTRODUCTION

A pulse generator was developed for driving the mod-anode of the cluster klystron. The main requirements are as follows:

<u>Parameters</u>	<u>Range</u>
Pulse voltage	30kV ~ 40kV
Pulse length	250 ns min, 600 ns max
Pulse polarity	Positive
Repetition rate	1 ~ 30 Hz
Load	Capacitive (30 ~ 100 pF, fed by a 90 cm long coaxial cable)
Size and weight	Light and compact is required, since all equipment have to be mounted inside the high voltage dome.

The initial design was made by J. Fischer¹. He used a Zarem circuit as a PFN (Pulse Forming Network) and a spark-gap as a switch. The trigger driver, EG&G TM-11A module, was employed.

We followed his scheme to continue the development in three stages.

Stage 1. Low voltage experiments. The purpose was to verify the circuitry principle, as well as find and solve the possible problems. To make things easier and safer, a very low voltage, no more than 50 V, and a mechanical switch was applied.

Stage 2. High voltage experiments. This was done with all the high voltage components enclosed in a shielding box, so that no high voltage can be exposed to human beings.

Stage 3. Final assembly and experiments.

1. Dr. Joachim Fischer deceased in Jan. 1995.

2. DESIGN CONSIDERATION AND BASIC PRINCIPLE

2.1. Design consideration

The pulse generator under developed is dedicated to drive the mod-anode, of which the function is to switch the beam from the magnetron injection gun. Normally, mod-anode does not interrupt any beam current, so that the load of the pulser is an open circuit except a capacitance. The latter consists of the capacitance between the mod-anode and the cathode and guard ring, as well as parasitic capacitance. The total is approximately 30 pF if one cathode is used, and increases to about 60pF if three cathodes are used. Besides, because the gun itself is mounted at the end of a "stalk", a rigid coaxial line inside the stalk connects the pulser and the mod-anode. The length of this coaxial line is about 38 inches, it causes about 3ns time delay, and it functions roughly as an extra capacitance. Since the diameters of the inner and outer conductors are 0.06 and 0.99 inches respectively, the characteristic impedance is 166 ohms. Correspondingly, the extra capacitance is about 20 pF.

Since both the conventional PFN and Blumlein PFN require matched loads, the Zarem¹ pulse generator was more desirable.

The schematic circuit of this pulse generator is shown in Fig. 1.

Fig. 1 The schematic circuit of the pulse generator

Obviously, the PFN is the key part of the pulse generator. In a conventional microsecond pulser it is usually formed by discrete components. In nanosecond pulser it can be a piece of cable. However, for a pulse of 300 ns, a cable would require a length of about 56 meters. Using discrete components is difficult, although it is not impossible if very delicate work is done, otherwise it will most likely result in poor performance. Therefore, a spiral delay line structure was

1. To our knowledge, the earliest circuitry of this type fit for mismatched load was designed by A. M. Zarem and his colleagues[1] in 1958. A Russian scientist Vvedenskii[2] also published a similar circuitry in 1959.

designed.

The spiral line is formed by a solenoid wound on a copper pipe. The copper functions as the ground. Note that it is not a common solenoid because there is no electromagnetic field at the axis, which has been shielded by the copper pipe. Instead, one can regard this as a long line above ground which has been wound to compress the physical size. The length of the wire wrapping on it determines approximately the delay time.

However, there exists coupling between different turns, and at the edge the coupling is different from that in the center, so this is, strictly speaking, a nonuniform transmission line. Therefore, this kind of spiral line PFN has a performance between a uniform transmission line and a discrete component PFN. On the whole, a spiral structure is simple, easy to do, and economic.

Another major concern is the switch. A thyatron is, of course, a good candidate. However, since a thyatron is usually operated at positive anode voltage, it produces a negative pulse on the load. A pulse transformer is thus necessary if a positive voltage is required on the load. A spark gap, on the other hand, can be operated in either polarity and a positive pulse can be delivered directly to the load, so that the transformer can be omitted. But, a spark gap, serving as a switch, has disadvantages. They are: it requires rather higher trigger voltage, the life time is relatively shorter, and especially, it has considerable delay time and jitter. Nevertheless, for the time being since the modulator is only being used for klystron R & D, these disadvantages seems tolerable.

2.2. Basic principle of Zarem pulse generator

For simplicity and also as in an ideal situation, the PFN can be represented by a transmission line with the same delay time. Fig. 1 is then replaced by the basic circuit shown in Fig. 2,

Fig. 2 The basic circuit of a Zarem pulse generator

where Z_0 is the characteristic impedance of the PFN and τ_0 its delay time. One end of the transmission line, point A, is connected to the load, Z_L . The other end is terminated by a matched resistor, i.e. $R_T = Z_0$.

The transmission line, PFN, is initially charged by the high voltage power supply $-V_0$, i.e. the capacitance between the wire and the copper with kapton as dielectric is initially charged, so that the upper line in Fig. 2 is at ground potential, while the bottom line is at negative potential.

When the switch K is closed, the bottom line suddenly drops to ground potential, the upper line becomes positive potential, and it then discharges from the both ends of the PFN.

During discharging, the voltage at the load is:

$$V_i = \frac{Z_L}{Z_L + Z_0} V_0 \quad (1)$$

As mentioned above, the load in our case is an open circuit¹, or $Z_L = \infty$. From (1), the load voltage is the same as the DC power source, but with a opposite polarity. Note that if the load is matched with the PFN, i.e. $Z_L = Z_0$, the load voltage will only be half the source voltage.

On the other end of the PFN is a matched load, i.e. $R_T = Z_0$, which absorbs all waves coming into it. In particular, the wave reflected from the open load will be totally absorbed. Thus the pulse duration is determined by the delay time of the PFN. Otherwise the energy will reflect back and forth from both ends causing a longer duration and an irregular waveform.

Briefly speaking, the Zarem circuit can be applied to any unmatched load. It produces a definite pulse length with a magnitude determined by equation (1). A capacitive load is also possible, but of course, the capacitance will inevitably smooth the pulse edge.

2.3 Comparison between different schemes

To review the advantages and disadvantages of different pulse generators, Table 1-1 lists the major concerns. The main advantage for choosing the Zarem circuit is that a matched load is not required. The disadvantage is that the energy is exhausted by the termination resistor rather than the load itself.

Table 1-1

	Conventional	Blumlein	Zarem
Output pulse voltage	$V_0/2$	V_0	V_0^a
Pulse length ^b	$2\tau_0$	$2\tau_0$	τ_0
Matched load required	yes	yes	no
Load resistance	Z_0	$2Z_0$	open ^c

a. The voltage depends on the load, listed here is in the case that load is open.

b. PFN delay time = τ_0 , for Blumlein there are two pieces of lines with τ_0 each

c. Open circuit is not necessary but a common case.

1. Except a capacitance, which we ignore at this moment for simplicity.

3. LOW VOLTAGE EXPERIMENTS

3.1. The experimental set up

The low voltage experiment was arranged in order to verify the circuitry principle, as well as to find and solve possible problems. Certainly, it is much more flexible and easier to do so at low voltage than at high voltage.

In order to meet the safety requirements, an experimental set up with a maximum voltage of only 50 V D.C. was employed. The schematic circuit is shown in Fig. 3-1. The key part is the PFN, which is formed by two solenoids, wound on two copper pipes with 9 layers of kapton, serving as insulation. The reason of using two instead of one solenoid is to compact the entire size. The solenoid is connected to a matched load at one end. The other end is the output connected to an oscilloscope in our case. A mechanical push button switch is employed. A 100 k Ω resistor is used to separate the PFN and the power source. It is also the charging resistance. All these are put into an aluminum box with appropriate insulation.

Fig. 3-1 The schematic circuit of the experimental set up

3.2 The experiments

A large number of experiments have been done^[1]. The basic principles were promptly verified in early experiments. They are summarized in the next paragraph. However, there existed a couple of problems. The two major concerns are that on the front edge of the pulse there always exists an oscillation, or ringing, and that on the rear top of the pulse there exists an overshoot, or a peak. (see Fig. 3-2). Besides, there is noise all the time, which exists in the oscilloscope because we triggered using a single shot so that it can not smooth it by averaging. This is only a problem of measurement and ignorable at this moment. The push button mechanical switch

Fig. 3-2 The effect of the cable length In time unit: (a) $\tau = 1$ nS; (b) $\tau = 3$ nS; (c) $\tau = 4$ nS; (d) $\tau = 15$ nS.

Fig. 3-3 The effect of the termination resistance: (a) $R_T = 99.5 \Omega$; (b) $R_T = 202 \Omega$; (c) $R_T = 221 \Omega$; (d) $R_T = 300 \Omega$.

was workable for our low voltage experiment, except that it had the disadvantage of poor stability that sometimes caused the waveform to be distorted due to imperfect closing of the switch.

Fig. 3-2 shows the effect of the length of the $50\ \Omega$ cable connected to the oscilloscope, which is equivalent to a capacitance load of the PFN in this case. As the figure shows, the longer the cable, the longer the pulse rise time. But, the period of the ringing does not depend on the length. It shows that the cable does not cause the ringing.

Fig. 3-3 shows the effect of the termination resistance. A mismatched terminating load will cause either a ladder waveform when $R_T > Z_0$, or an undulated form when $R_T < Z_0$.

A lot of effort was focused to find the cause of the ringing and its solution. Eventually, it was found to be due to the parasitic capacitance between the solenoid and the ground and the parasitic inductance in series with the switch. This will be discussed in the next section.

Concerning the overshoot on the rear top, initially we suspected there were some parasitic or non-uniformities at the termination end (R_T). But when we disconnected the two coils so that only one coil is connected with the output while the other end remained open, the overshoot still exists. Fig. 3-4 shows the result. Besides there are a series of pulses in sequence because both

Fig. 3-4 The pulse waveform of one solenoid with open ends.

Fig. 3-5 The transmission performance of the PFN

ends are open without energy absorber.

In order to get rid of any possible imperfection of the switch, and check if the rear top overshoot is an intrinsic feature of the PFN, the transmission performance has been tested. The PFN was connected directly to a pulse generator while we monitored its output without any switch. Fig. 3-5 shows the result. The input pulse is a square wave, (the lower pulse in the figure), while the output pulse has two equal oscillating waves near the beginning and the end. This is considered to be due to the non-uniformity of the solenoid since the inductance at both ends is less than that at the middle. We conclude the overshoot is not due to the switch but the PFN itself. The pulse delay in the Figure is also a measure of the delay time of the PFN.

Many compensating methods were tried and did show some improvement. However, the eventual set up at high voltage will be different. Though the main parameters should be the same, the parasitic parameters will change and affect the performance. So any compensation in the high voltage set up will make more sense than at low voltage. Thus we switched our effort to the high voltage experiment.

3.3 Brief summary

The low voltage experiments verified the principle of the Zarem type pulse generator:

- The pulse duration is exactly the delay time of the PFN, or the solenoid in our case;
- The magnitude of the pulse in the case of capacitive load is equal to that of the DC power supply, except the polarity is opposite;
- The rise time depends on the load capacitance;
- The transmission line, the coaxial line inside the stalk with length of about 3 nanosecond, is equivalent to an extra load capacitance and has no significant effect;
- The termination resistance will affect the tail waveform, namely a ladder form appears if $R_T > Z_0$, or an undulated form if $R_T < Z_0$.
- The ringing phenomenon is very common in pulse engineering and sometimes is very difficult to overcome. The ringing in our case is recognized to be due to the parasitic parameters connected with the switch and will be detailed in a separate section.
- The mechanical switch is believed to be good in a low voltage test.

4. THE ANALYSIS OF RINGING AND SIMULATION

4.1. Ringing analysis

Ringling is a very common occurrence in pulse measurement. However, the causes are quite different from case to case. Usually, the existence of parasitic parameters complicates the situation and results in unexpected performance. Also, it is one of the most common cause of the ringing. Therefore, serious attention must be paid to it.

As mentioned above, the ringing phenomenon was observed since the very first experiment. Many possibilities were investigated. Too fast a rise time of the pulse may cause easily a overshoot at the front edge, accompanied with a decaying ringing. But this is not the case here because the ringing appeared even during the rise time and the overshoot is not obvious. The irregularity of the PFN is unlikely to be the cause either, because lots of compensation methods were tried but couldn't cure it, though sometimes we got more or less improvement. The impedance mismatch between the PFN and the test cable or multiple reflections inside the cable were excluded too according to the experiments. Is the mechanical switch imperfect? Indeed the switch showed a certain poor repeatability in microsecond time structure, but the ringing phenomenon is by no means random. We tried different switches, including an electronic switch, but they didn't help. Then we had to check carefully all possible parasitic parameters.

Let's examine the physical structure of the circuit shown in Fig. 3-1. The PFN is formed by two copper pipes with wound solenoids, which make up the capacitance and inductance. The whole set up is put inside an aluminum box, which serves as the ground chassis. The copper pipes are initially charged to a DC high voltage via a 100 k Ω charging resistance. For an ideal situation, once the switch is closed, the potential of the copper will drop down to ground potential immediately. However, in practice this is not true. First, the switch has finite size and, especially, it needs wires to connect the pipe and the box, namely ground. The wires inevitably introduces inductance L_p . Second, besides the capacitance between the copper pipe and the solenoid, there is parasitic capacitance, C_p , between the pipe and ground. Once the switch is closed, an oscillation will occur between the C_p and the L_p . The equivalent circuit is shown in Fig. 4-1.

Fig. 4-1 The equivalent circuit with the parasitic parameters being taken into account

Evidently, since the copper pipe is not really grounded but has an oscillation voltage on it, this oscillation must overlap to the output pulse.

At first glance, the parasitic capacitance between the copper pipe and the ground may not be important because the solenoid in between may shield the field. However, the solenoid has considerable inductance, that can shield the DC field, but not the high frequency field

Let's now quantitatively estimate those parameters. The total parasitic capacitance C_p

Fig. 4-2 The model for calculating capacitance

consists of those between the copper pipe and the side wall and the bottom, as shown in Fig. 4. 2, i.e.

$$C_p = 2 (C_s + C_b) \quad (4-1)$$

The capacitance per unit length of a cylinder against a plane is given by^[4]:

$$C_1 = \frac{2\pi\epsilon_0}{\ln \frac{h + \sqrt{h^2 - a^2}}{a}} \quad (4-2)$$

where a is the diameter of the cylinder and h the distance between its center and the plane. The length of the copper in question is about 36 cm. From the dimensions shown in Fig. 4-2, it turns out $C_p = 60$ pF.

From the experiment, the period of the ringing is about 10 nS, corresponding to an oscillation wavelength of 3 meters, which is comparable with the length of the pipe. Thus if one takes into account the long-line effect, the effective capacitance is:

$$C_{p, eff} = C_p \cdot \frac{\tan \beta l}{\beta l} \quad (4-3)$$

where $\beta = 2\pi / \lambda$, l is the length of pipe. Substituting $\lambda = 3$ m, it turns out the effective capacitance is 74 pF.

To estimate the inductance is, however, less precise because of the irregular geometry. Assuming the wire has a radius 1 mm with a distance 5 cm against the wall, then the inductance per unit length is approximately:^[4]

$$L_1 \approx 0.01 \mu H/cm \quad (4-4)$$

In considering that the wire is only a few centimeters long, the calculated oscillation frequency is reasonably in conformity with the experimental results.

4.2 Experimental verification

In order to verify the above argument, an experiment has been arranged where the para-

Fig. 4-3 The variation of the ringing period with different wire length connected to the switch (the voltage is probed at the copper pipe)
(a) 5 cm; (b) 10 cm; (c) 15 cm; (d) 42 cm.

sitic inductance was changed artificially by means of changing the length of the wire. The results are shown in Fig. 4-3.

The experiments revealed clearly that the longer the wire the longer the period. Table 4-1 lists the oscillation periods related to the wire length. The inductances in the table are calculated according to these periods and the capacitance is assumed to be 74 pF. These values are lower than that calculated from the linear equation (4-4), because the latter refers to a straight wire, while in fact it is a curve. Therefore the results are reasonable.

Table 4-1

Wire length	Osc. period	Inductance
cm	nS	nH
5	12	4.9
10	17	7.3
15	20.9	11
42	35	28

The experimental results shown in Fig. 4-4 also give evidence that the oscillation in the copper pipe, the lower-curve in the figure, will also appear at the output pulse, the upper curve.

Fig. 4-4 The ringing exist in both the copper pipe and the output pulse

4.3 The simulation

Simulations have been done with code Micro-Cap IV. Fig. 4-5 is the circuit for simulation. The PFN is represented by 24 sections of L-C where the total inductance and capacitance are 62 μ H and 1680 pF respectively. The parasitic inductance is represented by L_1 . The parasitic capacitance is represented by 25 capacitors C_d , with 2.5 pF each, connected between each L-C node and the ground. This implies the capacitances are between ground and the solenoid. Physically it is reasonable, that initially they are not charged. However, from the point of view of oscillation, it plays the role of a capacitance C_p in Fig. 4-1.

Fig. 4-6 The ringing phenomena simulated by circuit (Fig. 4-5) with different parasitical inductance L1: (a) 0 μH ; (b) 5 μH ; (c) 10 μH ; (d) 15 μH ; (e) 30 μH .

Fig. 4-5 The circuit for simulation

Fig. 4-6 shows the simulation results. If $L_1 = 0$, there is no oscillation (see Fig. 4-6(a)). The larger the inductance L_1 , the longer the ringing period. This further verifies the cause of the ringing.

5. HIGH VOLTAGE EXPERIMENT

5.1. Spark gap experiment

The main difference between the low voltage and high voltage experimental set up, besides the necessity of insulation, is the switch. Not only is its size much larger for high voltage, which introduces different stray impedance, but also the performance of the switch itself is quite different from type to type. In fact, for a high voltage pulse generator the switch is of major concern, and usually a limiting factor. In our case the EG&G spark gaps, GP-41B (for 30 kV) and GP-32B (for 40 kV), were used. It is appropriate to check their performances before going on to an entire set up.

First of all, we checked the trigger pulse of the EG&G trigger driver TM-11A without load. The result is shown in Fig. 5-1^[10]. Its magnitude of 30 kV is large enough, but the rise time is on the order of microseconds. This is too long for triggering a pulse of 300 ns since it may cause

Fig. 5-1 The trigger pulse shape

too much jitter. However, we couldn't get a better one at this time and since jitter is not a serious issue for the purpose of test only, we used it in all the experiments.

To check the spark gap, the simple test set-up shown in Fig. 5-2 was employed. A capacitor of 1200 pF was used instead of the PFN. It connects with a resistance load to form an R-C discharge circuit. A voltage divider is used to meet the safety requirement that the maximum charging voltage is within the limit of the probes. The trigger driver can supply both polarities, but was applied positive in this experiment according to the manufacturer's recommendation.¹ All parts having exposed high voltage, including probes, are put inside a shielded high voltage box.

Two problems were raised in the experiments. One problem is that a "skirt" always appears before the main discharge. The second problem is the delay time between the two breakdowns, namely, the breakdown occurs at first at the gap between the trigger electrode and

1. This was eventually changed to negative to improve the performance, see later.

Fig. 5-2 The spark gap test set up

adjacent electrode, and then occurs at the gap between the opposite electrode and the adjacent electrode.

Fig. 5-3 ^[11] shows the discharge pulse. A skirt clearly appears before the discharge. The discharge comes from the closing of the switch. However, the skirt has a random shape and is considered a partial discharge.

Fig. 5-4 ^[12] shows the discharging pulse accompanying the trigger pulses. The trigger voltage suddenly drops down, indicating a breakdown occurrence. The sharp increase of the discharging current indicates the breakdown of the main gap. The latter has a random delay time relative to the trigger breakdown, ranging from 40 to 110 ns. In a later high voltage PFN experiment we observed a maximum delay of 160 ns. ^[14] In fact the trigger pulse is applied on the trigger electrode causing a breakdown at the nearest electrode, i.e. the adjacent electrode. Then the arc expands to the main gap --- between opposite electrode and the adjacent gap.

Fig. 5-5 ^[13] shows that the breakdown voltage is related to the main high voltage (i.e. V_c on the Fig. 5-2). On it there is an additional trigger pulse (left upper curve), where no main high voltage is applied on the opposite electrode, i.e. $V_c = 0$. It breaks down at about 10 kV. When $V_c = 30$ kV, (left lower curve) the trigger breakdown voltage is about 6 kV. The higher the V_c , the lower the trigger breakdown voltage, and the shorter the delay time. Table 5-1 gives an example. However, keep in mind all those data are random.

Table 5-1

Voltage V_c (on main gap)	Breakdown Voltage (Trigger breakdown)	Delay time
40 kV	7.0 kV	60 ns
30 kV	8.8 kV	110 ns

Fig. 5-3 The R-C discharge form, a random "skirt" is shown at front edge.

Fig. 5-4 The delay time between trigger breakdown and the main gap breakdown with the main high voltage is 30 kV (left) and 40 kV (right)

Fig. 5-5 The discharge pulse (right), and the trigger pulse (left). The trace on the upper left is the trigger pulse when the main high voltage is not on.

In all cases the breakdown voltage is much lower than the 30 kV that the trigger driver TM-11A can supply. However, it may increase gradually along with its lifetime. Though one spark gap is capable of operating at both 30 and 40 kV, it is hard to optimize the performances over a wide range.

5.2 PFN high voltage experiment

The set up for the PFN high voltage test is similar as that for the spark gap test, except the capacitance is replaced by the PFN. The PFN and the spark gap are put inside an oil tank. The wiring is made as short as possible, but is still longer than that in low voltage test. Fig. 5-6 shows this scheme.

Fig. 5-6 PFN high voltage test set-up

Not surprisingly, the phenomena discovered in the low voltage test and the spark gap test are also observed in the high voltage test. But there are also some new phenomena. Fig. 5-7 gives an example^[14]. The major concerns are as follows:

1. Ringing appears on the top of the pulse. Since the parasites related to the switch are inevitable and even larger than those in the low voltage test, as mentioned earlier, this is not surprising. Nevertheless, it is expected to be damped by a resistance in series with the switch. Besides, we also expect it will be smoothed due to the additional load capacitance introduced by the stalk coaxial line.

2. There exists also a random delay. It is of concern if jitter is important. The issue of jitter will be addressed later.

3. The "skirt" before the pulse appears most of the time. It is recognized to be an imperfection of the spark gap.

Fig. 5-7 An example of the high voltage pulse. The trigger pulse is on the left.

4. On the top of the pulse, there is a “deficiency” on the rear part. Interesting enough, no matter what the skirt shape is, if one cuts the “skirt” and amends it to the “deficiency”, it will just fit. This puzzle was eventually recognized to be an intrinsic character of the Zarem circuit. The detail of both theory and experiment is addressed separately.

5.3. Jitter

As mentioned above the output pulse has a random delay. In fact, the delay time as well as the breakdown in the spark gap depends on many factors: the type of the spark gap (with different gas medium and pressure), its age, the voltage level on the opposite electrode, (an example has been shown in Fig. 5-5), the pulse repetition rate, the environment, and especially, the trigger pulse. In our experiment, the trigger driver TM-11A generates a pulse with a duration time more than 1μs and the rise rate of 3.4 kV/mS to 6 kV/mS. So the trigger time can hardly be precise on a scale of nanoseconds. Nevertheless, a test of the jitter time was arranged. Fig. 5-8 gives an example^[15].

It can be seen in the Fig. 5-8, there are two time delays. One is the time between the trigger breakdown at the adjacent electrode and the trigger pulse start time, t_{trig} . The second is the time between main gap breakdown and the trigger pulse start time, t_{mg} . What we discussed before is their difference, $\Delta = t_{\text{mg}} - t_{\text{trig}}$, which was observed directly from the oscilloscope. However, of most concern is the jitter of the main pulse, namely the jitter of t_{mg} . This jitter depends on the characteristics of the spark gap, and the trigger driver. Besides, a datum of jitter must be referred to a certain condition. For example, if a spark gap is operated at a voltage close to its lower limit, the jitter may be very large, but if the same device is operated close to its high voltage limit, the jitter is expected to be much less.

Fig. 5-8 An example showing the delay time for the test of jitter

In order to measure the jitter, the test set up was set in a definite condition. The spark gap under test is GP-41B. The high voltage was of 30 kV. A high voltage capacitor of 100 pF was connected to the spark gap in parallel to speed up the main gap breakdown. The trigger driver

Table 5-2 Jitter test

Sequence Number	Breakdown time (ns)		Δ
	Trigger	Main gap	ns
	t_{trig}	t_{mg}	$t_{mg} - t_{trig}$
#1	880	920	40
#2	960 (max)	1040 (max)	80
#3	880	940	60
#4	800 (min)	880 (min)	80
#5	940	970	30
#6	900	960	60
#7	880	950	70
#8	900	960	60
#9	920	1000	80
#10	960	1010	50
Jitter time	160	160	50

was set at its maximum output. The oscilloscope was set at 200 ns per division and a constant trigger condition. We assumed it was stable related to the trigger pulse for different shots. Thus we ignored the possible jitter of the oscilloscope itself. From the observations this assumption is reasonable. A series of tests were recorded, as shown in Table 5-2.

It indicates that both the trigger breakdown and the main pulse have a jitter in the range of 160 ns. Since the number of measurements is limited, this is not a precise conclusion.

5-4. The improvements and the final result

As mentioned above, the output pulse always has a "skirt" before the front edge accompanied with a "deficiency" on the rear top with the same shape. A deep analysis ^[17] indicates the skirt is due to the imperfection of the spark gap, while the accompanied deficiency is an intrinsic feature of the Zarem type pulse generator.

The skirt appears after the trigger breakdown and before the main gap breakdown. Though the delay time is random, it is found when the applied voltage is close to its upper limit, the main gap breakdown is faster. Certainly the breakdown is dependant on the voltage. In order to speed up the breakdown process, we tried to connect a capacitance in parallel with the spark gap. Because the capacitance is charged with high voltage, will sustain a higher current and provide more energy early in the breakdown so as to speed up the process. Experiments showed a slight improvement.

Later on we realized that the skirt is mainly due to a "cross interaction" between trigger electrode and the opposite electrode.

The process is this. At first, the gap between trigger electrode and the adjacent electrode breaks down after the trigger pulse is applied. Second, the gap between trigger electrode and the opposite electrode breaks down. At this stage, because the area of the trigger electrode is very small, the discharging current is limited, unlike a full breakdown. This is "cross interaction". This partial discharge occurs at both end of the PFN. In the output end it causes a skirt, while at the other end it causes a deficiency.^[17] After the arc expands, the gap between opposite electrode and the adjacent electrode breaks down. Only at this moment the spark gap becomes completely closed.

Based on this understanding, we investigated an alternative trigger mode, where the trigger is exerted with a negative pulse, the same polarity as the opposite electrode, so that the voltage between the trigger electrode and the opposite electrode during breakdown is less than at main gap and will not cause cross interaction between them.

The result is much better. Fig. 5-9 shows the final result^[16]. The skirt disappears. In this case, a damping resistance of about 10 ohm is used.

Fig. 5-9 The output pulse when the trigger pulse is negative.

From Fig. 5-9 one can still see the noise and some distortions. The noise is due to the oscilloscope itself. Because the measurement is on the single shot, the waveform can not be smoothed by averaging. Also, there are some error due to the high voltage probes, they pick up the spray field and make the pulse form a little distortion.

For the time being, we are waiting for the mechanic parts for the final assembly. Of course, a final trim is necessary before commissioning.

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