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Design and Measurements of A Pulsed Beam Transformer as a Chopper

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Abstract

A pulsed beam transformer is proposed for a beam chopper. It has fast rise- and fall-time and a short physical length. Measurements were carried out using a kicker power supply. A test cavity was constructed. Two types of materials were tried for the magnetic core of the cavity — the Finemet and 4M2 (a ferrite). While the former gave good performance, the latter failed the test. A high voltage, fast repetition rate bipolar power supply is being built. Beam tests are planned.

1 Introduction

In a high intensity proton accelerator, a beam chopper is often necessary in order to reduce particle losses during injection from the linac to the first circular machine. A chopper can also serve other purposes such as to create a gap in a bunch train so that the extraction loss due to kicker rise-time can be eliminated.

There are various ways to chop the beam, *e.g.,* ion source chopping, [1]-[2] transverse deflecting,[3] *etc.* This paper introduces a new type of chopper, which is similar to a *beam transformer* first discussed by R. Wideroe.[4] It is based on the fact that the RFQ has a rather small energy window. Both simulations and measurements show that, a $\pm 10\%$ energy error in a beam before it enters the RFQ can effectively cut the transmission efficiency down to zero.[5]-[7] For an RFQ with an injection energy of 50 keV, a 10% error is 5 keV. Therefore, a pulsed beam transformer that provides a 5 keV energy modulation to the beam in front of an RFQ can serve the purpose of a chopper. There are several advantages of this type of chopper.

1. Fast rise- and fall-time.
   This is important for reducing injection losses. When the chopping is done in a surface type of H^- ion source, it is difficult to have a rise-time shorter than 50 ns. In a volume type of H^- ion source, the rise-time will be longer. When a pulsed beam transformer is used, the rise- and fall-time is mainly determined by the switch speed. As will be seen in Sec. 3, a 40 ns rise-time has already been achieved when a thyratron is used. It is expected that a solid state switch (*e.g.*, the HTS transistor) will be even faster.

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2. Short physical length and chopping at low energy.
   A transverse deflector has a fast rise-time. But its length is usually over one meter. Because of the space charge problem, it can not be placed in front of an RFQ. For a low energy RFQ, say 750 keV, a deflector can be installed after the RFQ and will chop the beam at that energy. For a high energy RFQ, say 3 MeV, this method becomes difficult. On the contrary, the length of a beam transformer can be made as short as 10 cm. Therefore, it can be installed between the LEBT (low energy beam transfer) and RFQ. It will chop the beam at a much lower energy, *i.e.,* at the RFQ injection energy (which is 50 keV at the JHF).

2 Design

2.1 Components of a chopper

The chopper consists of a pulsed power supply and a cavity. The latter contains several magnetic cores and works as a transformer. When a voltage waveform is provided in the primary circuit, an acceleration or deceleration voltage with the same waveform will be generated across the gap as the secondary. An ideal voltage waveform is a series of squares, each with steep rise and fall edges and a flat top. The height of the square is 5 kV (which could be a bit higher or lower, depending on the design of the RFQ). The repetition rate (rep rate) of the squares are determined by the injection rf frequency. The spacing between two neighboring squares is equal to the chopped beam length.

It is necessary to use a bipolar waveform instead of a monopolar one. The reasons are: (1) A monopolar waveform will generate significant flyback voltage on an inductive load when the power supply is switched off; (2) A monopolar waveform has a significant dc component, which is not useful for acceleration. It should be pointed out, however, that even with a bipolar waveform there may still be some dc component if the chopping length is not half of the period.

Take the JHF as an example. The bucket length of the JHF Booster at injection is 500 ns (2 MHz). Assume one-half of the beam will be chopped. The required voltage waveform is as follows: +2.5 kV for 250 ns, -2.5kV for the next 250 ns in a period of 500 ns. When this voltage is transmitted to the beam through an accelerating gap, the beam energy will alternate between E_{H^-} + 2.5 keV and E_{H^-} − 2.5 keV, where E_{H^-} is the H^- ion source energy. If the injection energy of the RFQ is 50 keV, E_{H^-} can be set to 47.5 keV. Thus, at the exit of the RFQ, a 250 ns gap will be created in the beam every 500 ns.

2.2 Magnetic core

The magnetic core is a critical part of the beam transformer. It must be able to stand high magnetic field B_{rf} and must have high permeability μ. Two types of materials have been tested for making the core — the Finemet and the Philips 4M2 (which is

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a ferrite). Their magnetic parameters can be found in Ref. [8].

2.2.1 Requirement of high B_{rf}

When a voltage waveform $v(t)$ is applied, the flux in the core is:

$$\phi = \int v(t)dt \tag{1}$$

For a square voltage pulse of height 5 kV and length 250 ns, the flux is 1.25×10^{-3} Weber. The average B-field is:

$$B_{ave} = \phi/A \tag{2}$$

in which A is the flux area of the core. The maximum B-field is:

$$B_{max} = B_{ave}\frac{OD - ID}{ID \ln \frac{OD}{ID}} \tag{3}$$

in which OD and ID are the outer- and inner-diameter of the core, respectively. Because the Finemet can be used at much higher B_{ave} ($\sim$ 2 kG or higher) than that for the 4M2 ($\sim$ 100 G), it makes the Finemet a preferred candidate of the core. As an illustration, assume the following core dimensions: OD = 50 cm, ID = 20 cm, d = 2.5 cm, where d is the thickness of a core. To provide a flux of 1.25×10^{-3} Weber with the constraint of B_{ave} mentioned above, two Finemet cores would suffice, compared to 34 cores that would be needed if the 4M2 is used.

2.2.2 Requirement of high μ

The inductance of a magnetic core is:

$$L = \frac{1}{2\pi}\mu d \ln \frac{OD}{ID} \tag{4}$$

High μ gives large L. It is needed for two reasons:

1. The decay time constant τ on the flat top is associated with L/R, where R is some equivalent resistance that will be discussed later. A larger L means a flatter top.

2. When τ is much larger than the pulse length t_0, the current is given by

$$I_L = \frac{Vt_0}{L} \tag{5}$$

   A larger L means a smaller current, which is important in the power supply design.

As will be seen in Sec. 2.4, in the frequency range near 2 MHz or below, the Finemet has a much higher μ than the 4M2. This is another reason why the Finemet is a better material than the 4M2 for a chopper.

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2.3 Pulsed power supply

The power supply is a bipolar voltage source. It provides $\pm\frac{1}{2}V_0$ square pulses at a given rep rate (2 MHz for the JHF). The number of pulses in a burst is determined by the injection time. It is about 0.3 ms for the JHF, which corresponds to 600 pulses. The relative length of $+\frac{1}{2}V_0$ and $-\frac{1}{2}V_0$ should be a variable so that the chopping length can be adjusted to meet different needs at the injection.

The switch is the most important part of the power supply. It must be able to deliver high voltage (several kV), high current (several tens of amperes) at high rep rate (several MHz). It must also have short turn-on and turn-off time (a few tens of nanoseconds). Thyratron has very low rep rate (several Hz) and is thus ruled out. (However, it was used in the proof-of-principle measurements, see Sec. 3.) There are some triodes and transistors that are commercially available and can serve the purpose, for example, the fast high voltage transistor switch HTS 81-09 from a German company Behlke.[9]

The peak power of the power supply is high (hundreds of kW). But the injection time is short compared with the cycle time. Therefore, the duty factor is low. For the JHF, the duty factor is below 1%.

2.4 Fourier spectrum of a square waveform

Either the Finemet or the ferrite is a non-linear magnetic material. Their permeability has a strong dependence of the frequency. In order to estimate their inductance, one needs to know the Fourier spectrum of a square waveform.

2.4.1 Discrete spectrum

Assuming the pulse has a period $\omega_0 T = 2\pi$ and a length of 2α as shown in Figure 1, it has the following discrete spectrum:

$$V(\omega_0 t) = V_0 \frac{2\alpha}{\pi}\left(\frac{1}{2} + \sum_{n=1}^{\infty} \frac{\sin(n\alpha)}{n\alpha}\cos(n\omega_0 t)\right) \tag{6}$$

(The dc term will be much smaller than $V_0\alpha/\pi$ in bipolar operations.) The spectrum lines are $n\omega_0$, $n = 0, 1, 2, \ldots$ When α is large, high frequency components are small. When α becomes smaller, high frequency components will become larger. But still, the locations of these lines remain the same.

For the JHF, $T = 500$ ns, $\omega_0 = 2\pi\times$ 2 MHz. Thus, the permeability value at 2 MHz gives a reasonable first estimate. The measured permeability of the Finemet at this frequency is about 2800 (in a parallel equivalent circuit representation), whereas that of the 4M2 is about 170. This difference leads to the different performance of the two materials in the experiments of Sec. 3.

2.4.2 Continuous spectrum

When the period T gets longer, ω_0 gets smaller. The whole spectrum will be shifted towards the lower end. In the extreme case of a single pulse, $T \to \infty$, $\omega_0 \to 0$, $\alpha \to 0$,

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while $\frac{\alpha}{\omega_0} \rightarrow \frac{t_0}{2}$, where t_0 is the length of the single pulse. Then the discrete spectrum becomes a continuous one:

$$\mathcal{V}(\omega) = V_0 \frac{2\sin\left(\frac{\omega t_0}{2}\right)}{\omega} \tag{7}$$

It has nodes at $\omega = \frac{2n\pi}{t_0}$, $n = 1, 2, \ldots$

For a single pulse of a length of 250 ns, which was used in the experiments below, the first node occurs at 4 MHz.

3 Measurements and analysis

3.1 High voltage, low rep rate measurements

3.1.1 Test cavity and power supply

In order to demonstrate the feasibility of such a chopper, a simple cavity was constructed as shown in Figure 2. It consists of a magnetic core, a copper shield, a one-turn coil (the primary circuit of the beam transformer) and a stainless steel beam pipe. The pipe has a 22-mm long ceramic gap for acceleration or deceleration (the secondary of the transformer).

Because there is no high voltage, high rep rate pulsed power supply that can be available to us at this time, a high voltage, low rep rate (3 Hz) kicker power supply was used in the experiment. This is a monopolar voltage source. It uses a thyratron as the fast switch and a pulse forming line (PFL) with a characteristic impedance 25 Ω. A dummy load of 25 Ω is added in parallel to the primary circuit for matching the PFL impedance.

3.1.2 Circuit model

To analyze the transient process when the switch is turned on or off, a circuit model for this experiment is used, which is shown in Figure 3(a). Because the beam current (tens of mA) is much smaller than the primary circuit current (tens of amperes), the beam loading voltage is negligible. In other words, this can be treated as a "no load" transformer. This model has a high voltage source V_0 (which could be a large charging capacitor), a fast switch, an internal resistance, a characteristic impedance of the PFL, a matching resistance (the dummy load), a RC snubber for reducing the flyback voltage, a gap capacitance, and an equivalent parallel LR circuit representing the magnetic core. This model is further simplified to the one as shown in Fig. 3(b), which is easier to be analyzed. The conversion from Fig. 3(a) to 3(b) is straightforward.

1. Switch-on:
   The current and voltage of the inductance load are, respectively,

$$i_L(t) = \frac{V_0}{R_1}\left(1 - e^{-t/\tau}\left(\cos\omega t + \frac{1}{\omega}\left(\frac{1}{\tau} - \frac{1}{\tau_L}\right)\sin\omega t\right)\right) \tag{8}$$

$$v_L(t) = V_0\left(\frac{R_2}{R_1 + R_2}\right)e^{-t/\tau}\left(\cos\omega t + \left(\omega\tau_L + \frac{1}{\omega\tau}\left(\frac{\tau_L}{\tau} - 1\right)\right)\sin\omega t\right) \tag{9}$$

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in which

$$\frac{1}{\tau} = \frac{1}{2}\left(\frac{1}{\tau_L} + \frac{1}{\tau_C}\right) \tag{10}$$

$$\tau_L = \frac{L}{R_p} \tag{11}$$

$$\tau_C = CR_s \tag{12}$$

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} \tag{13}$$

$$R_s = R_1 + R_2 \tag{14}$$

$$\omega = \sqrt{\omega_0^2\left(\frac{1}{1+\frac{R_2}{R_1}}\right) - \left(\frac{1}{\tau}\right)^2} \tag{15}$$

$$\omega_0 = \sqrt{\frac{1}{LC}} \tag{16}$$

It is seen that there are two relevant time constants: τ_L (L in parallel with R_1 and R_2) and τ_C (C in series with R_1 and R_2). The overall time constant τ is a combination of the two. In this process, τ should be much larger than the pulse length so that the voltage waveform top can be kept flat.

2. Switch-off:

$$i_L(t) = I_{L0}e^{-t/\tau}\left(\cos\omega t - \frac{1}{\omega\tau}\sin\omega t\right) \tag{17}$$

$$v_L(t) = -I_{L0}R_2e^{-t/\tau}\left(\cos\omega t + \frac{1}{2}\left(\omega\tau - \frac{1}{\omega\tau}\right)\sin\omega t\right) \tag{18}$$

in which I_{L0} is the initial current in the inductance load when the switch is turned off, and

$$\tau = \frac{2L}{R_2} \tag{19}$$

$$\omega = \sqrt{\omega_0^2 - \left(\frac{1}{\tau}\right)^2} \tag{20}$$

$$\omega_0 = \sqrt{\frac{1}{LC}} \tag{21}$$

In this process, τ should be small in order to avoid oscillations.

3.1.3 Results of the measurement

Both the Finemet and 4M2 were tested. The dimensions of the Finemet core are: $OD = 58$ cm, $ID = 32$ cm, $d = 2.5$ cm. That of the 4M2 are 50 cm, 20 cm and 5 cm, respectively. The measured primary and secondary (*i.e.*, the gap) voltages are shown in Figures 4-6.

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- Finemet:

  1. It is seen that the gap voltage has a nearly square shape. The rise-time is about 40 ns, which is determined by the thyratron. The fall-time is a bit longer.
  2. The amplitude difference between the primary and secondary voltage is small, which indicates good coupling.
  3. In Fig. 4, the measured primary voltage is about 2.25 kV, the measured total current is about 150 A. It is known that, at 2 MHz, the inductance of this Finemet core is about 8.35 μH. Thus,

$$\begin{aligned} I_L &= \int v(t)dt/L = 54 \text{ A} \\ I_R &= V/R = 90 \text{ A} \quad (R = 25\ \Omega) \\ I_{total} &= I_L + I_R = 144 \text{ A} \end{aligned}$$

     The calculated current agrees with the measured value of 150 A.
  4. In Fig. 5, the maximum gap voltage reaches about 7.5 kV. The corresponding primary voltage is about 8 kV. In this case, one has $B_{ave} = 4.9$ kG and $B_{max} = 6.7$ kG. (Eqs. (1)-(3))

- 4M2:

  1. In Fig. 6, it is seen that there is a fast fall off in the voltage waveform after the switch is turned on. There are two reasons for this behavior:
     (a) The inductance of the 4M2 is smaller than the Finemet, the decay is faster.
     (b) The maximum B_{rf} of the 4M2 is rather low ($\leq$ 100 G). At high voltage, which means high B_{rf}, the performance of the 4M2 is deteriorated.
  2. When the switch is turned off, there is a voltage jump to the opposite side with an amplitude equal to V_0.
  3. In the 4M2 experiment, the secondary voltage was measured using a one-turn coil instead of a ceramic gap, and there was no snubber circuit. Therefore, both C_g and C_b in Fig. 3(a) are absent in this case. It is equivalent to $C = \infty$ in the simplified circuit model Fig. 3(b). It is known that $R_1 = R_2 = 25\ \Omega$, $L = 2\ \mu$H (measured). Thus the calculated decay time constant τ when the switch is turned on is 160 ns. As a comparison, the measured time constant in Fig. 6 is about 200 ns. Both are in general agreement.

     During this measurement, there was a drift in the baseline. Therefore, it is difficult to measure the time constant when the switch is turned off.

3.2 Low voltage, high rep rate measurements

In these measurements, two waveform generators were separately used as the power supply. One is bipolar ($\pm$5 V), another monopolar (up to about 100 V). The measurements were done at 2 MHz and 7 MHz. Some results are shown in Figures 7-9.

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- Finemet:
  It is seen in Figs. 7 and 8 that both the primary and secondary voltage have a nice square shape. The overshooting can be minimized by means of a resistive terminator. The price to pay for this is that more current from the power supply will be required.

- 4M2:
  There is again a fast fall off as shown in Fig. 9. In this experiment, B_{rf} is low. The fall off is attributed to the low permeability.

4 Plan for beam tests

A new power supply and a test model of the chopper have been designed. The power supply will use two HTS 81-09 transistors for a bipolar operation, as shown in Fig. 10. Each transistor can operate at 8 kV, 90 A at a burst frequency of 2.5 MHz. The pulse length can be varied from 200 ns to infinity.

The chopper will use three Finemet cores. The dimensions of each core are: OD = 50 cm, ID = 16 cm, d = 2.5 cm. The total inductance at 2 MHz is about 50 μH. The total length of the chopper is about 10 cm.

It is important to minimize the parasitic capacitance in the chopper. The ceramic gap has a capacitance of 10 pF. The resonance frequency would be 7 MHz for a 50 μH inductance. However, the Finemet is a non-linear material. Its inductance will be only about one-third of 50 μH at 7 MHz. Therefore, the actual resonance frequency of this chopper is expected to be above 10 MHz.

This chopper will first be installed on the KEK-PS beam line for beam energy modulation test. If it works well, it can be moved to the JHF 5 MeV test linac for a beam chopping experiment.

5 Conclusions

1. It is feasible to construct a beam transformer to provide 5 kV (or higher) pulses with short rise- and fall-time and with a flat top. When it is placed in front of an RFQ, it can be used as a beam chopper.

2. The Finemet has high B_{rf} and high μ. It is a good material for the magnetic core of the chopper.

3. The ferrite Philips 4M2 gave poor performance in the tests. This is because its B_{rf} and μ are too low to meet the requirement.

4. The measurement results are in general agreement with analysis.

5. A bipolar high voltage source with high current and fast switches is the preferred power supply.

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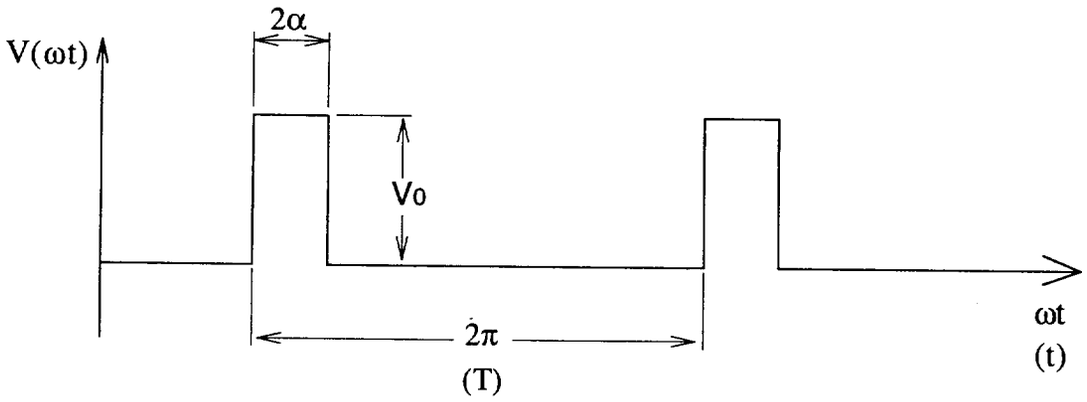

Figure 1: A series of voltage pulses with square waveform. The period is $\omega_0 T = 2\pi$. The length of each pulse is 2α.

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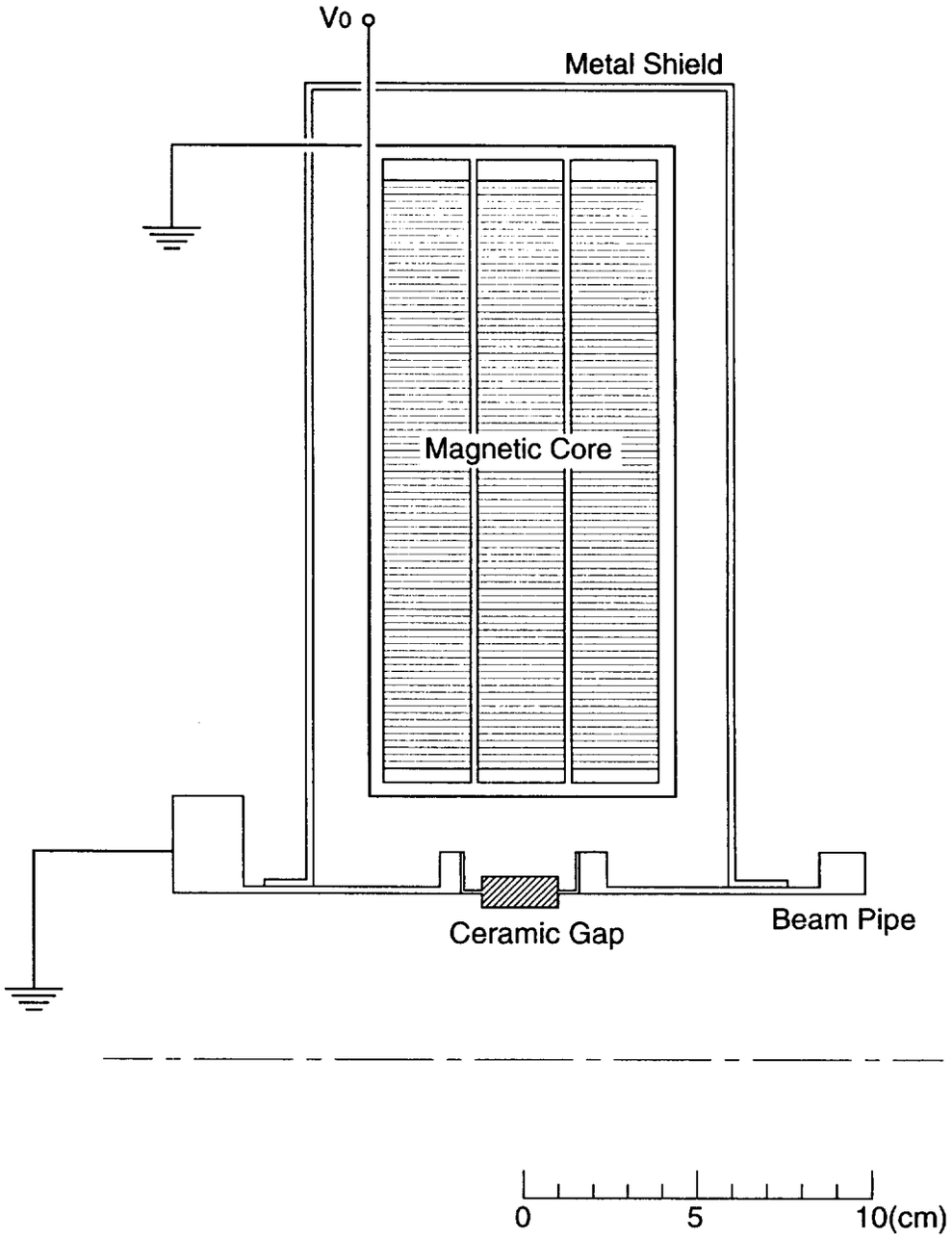

Figure 2: A test cavity used in the measurements. It consists of a magnetic core, a metal shield, a one-turn coil (the primary circuit of the beam transformer) and a stainless steel beam pipe. The pipe has a 22-mm long ceramic gap for acceleration or deceleration (the secondary of the transformer).

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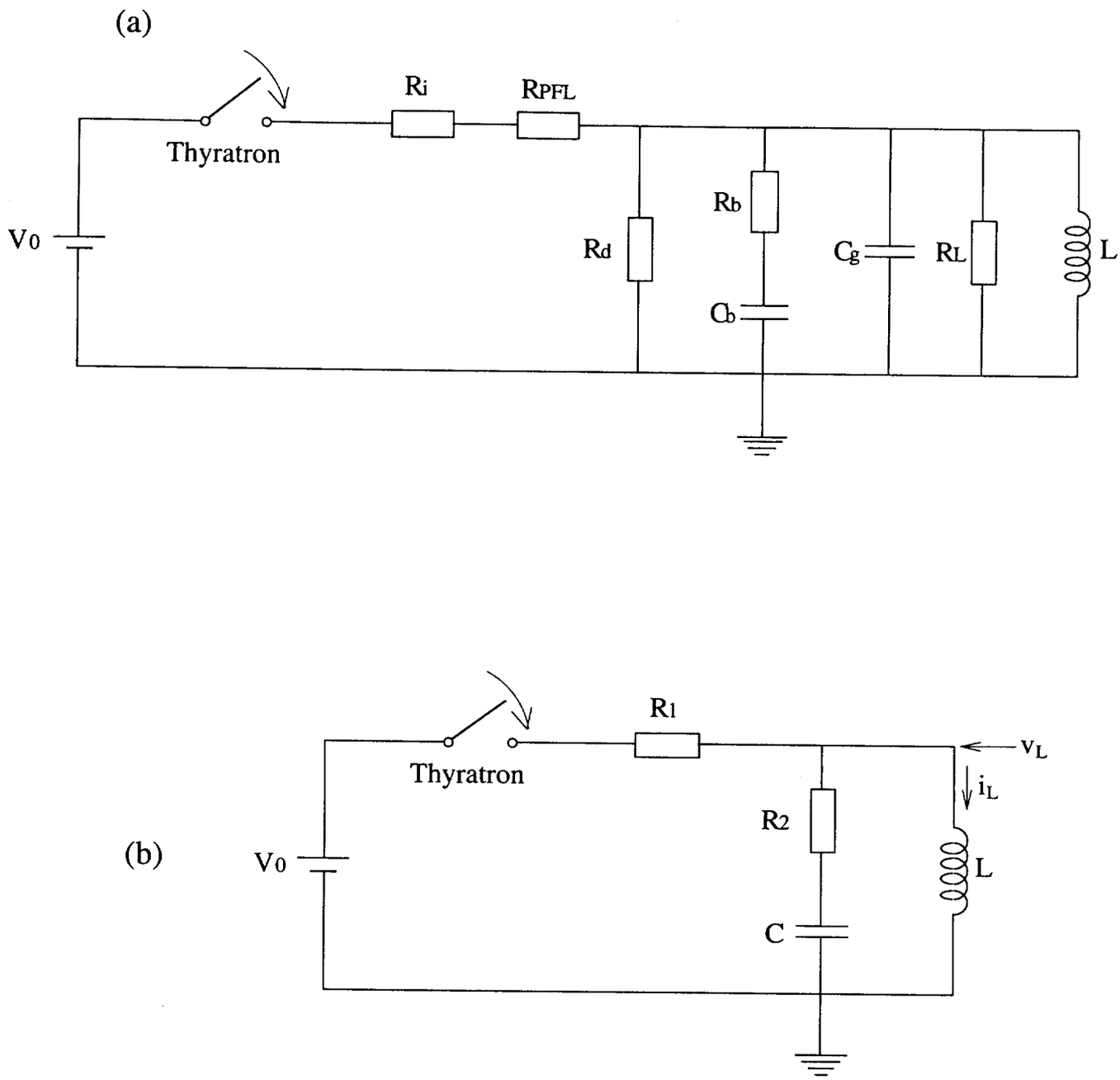

Figure 3: (a) A circuit model of the measurements. It has a high voltage source V_0, a fast switch, an internal resistance R_i, a characteristic impedance of the PFL R_{PFL}, a dummy resistance R_d, a snubber circuit R_bC_b, a gap capacitance C_g, and a parallel LR_L circuit representing the magnetic core. (b) A simplified equivalent circuit used in the analysis.

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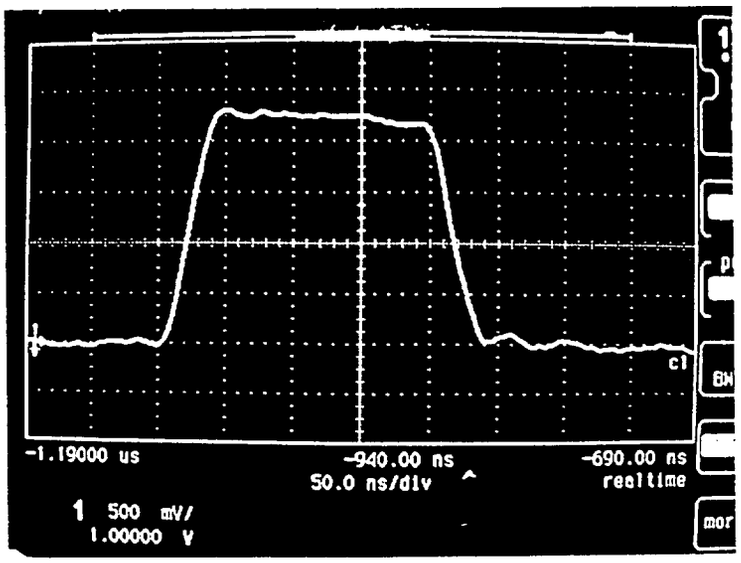

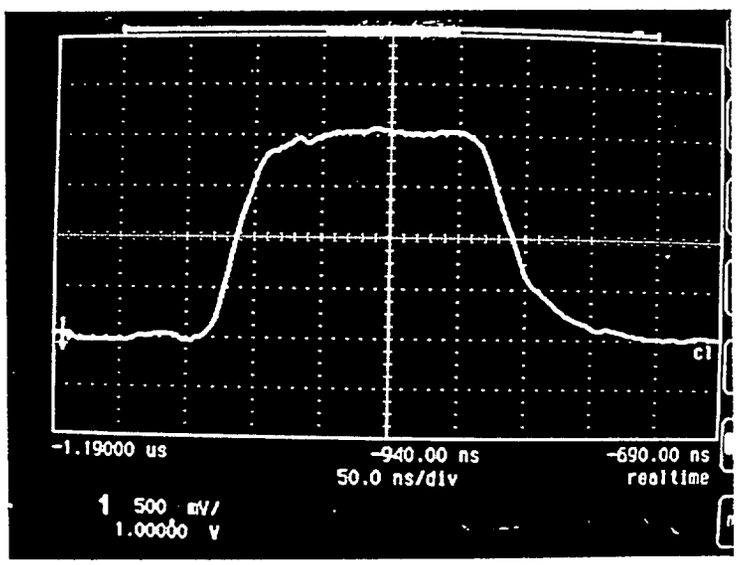

Figure 4: The primary and secondary voltage waveform when a Finemet core and a monopolar high voltage source are used. The rep rate is 3 Hz. The rise-time is about 40 ns. The primary voltage is about 2.25 kV, the secondary about 2 kV. The measured total current from the power supply is about 150 A.

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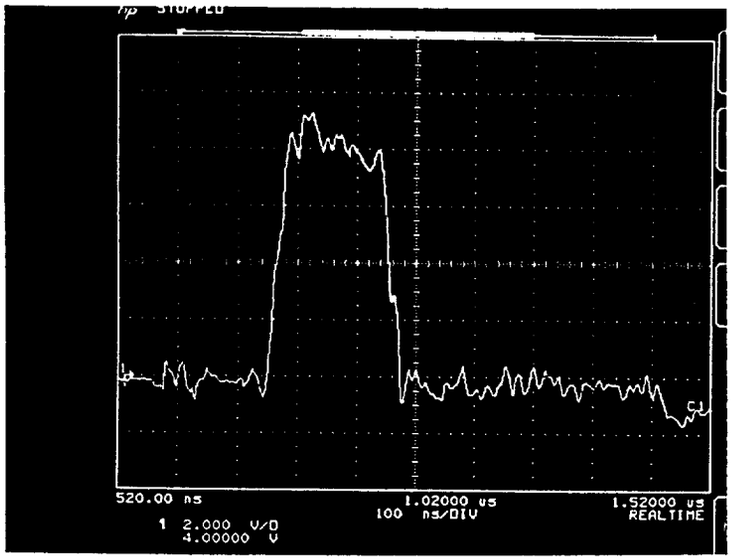

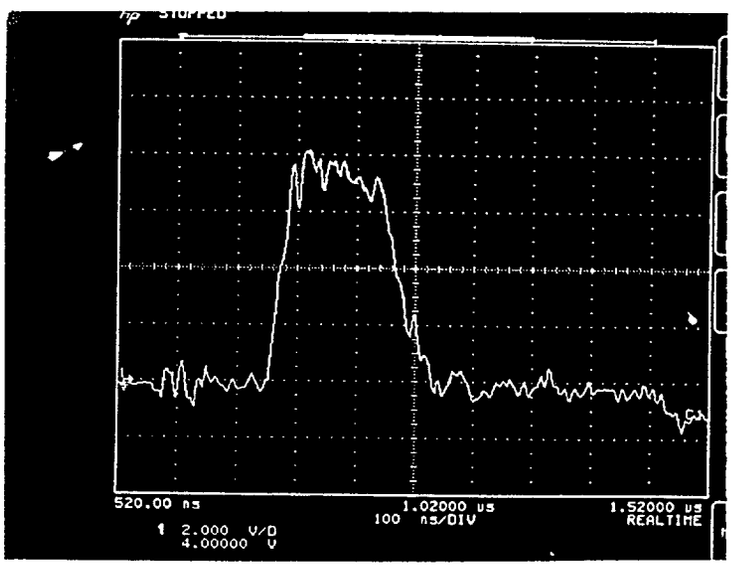

Figure 5: The maximum primary and secondary voltage (8 kV and 7.5 kV, respectively) obtained in the measurement when a Finemet core is used. The corresponding B_{ave} is 4.9 kG and B_{max} 6.7 kG.

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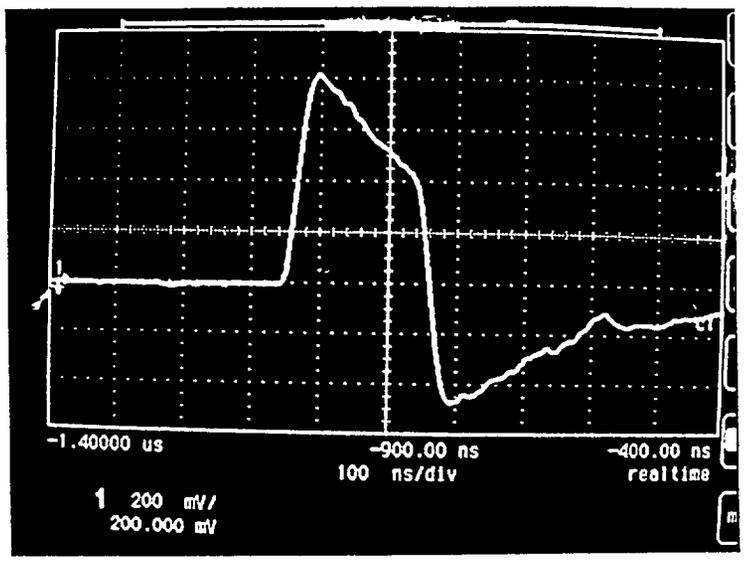

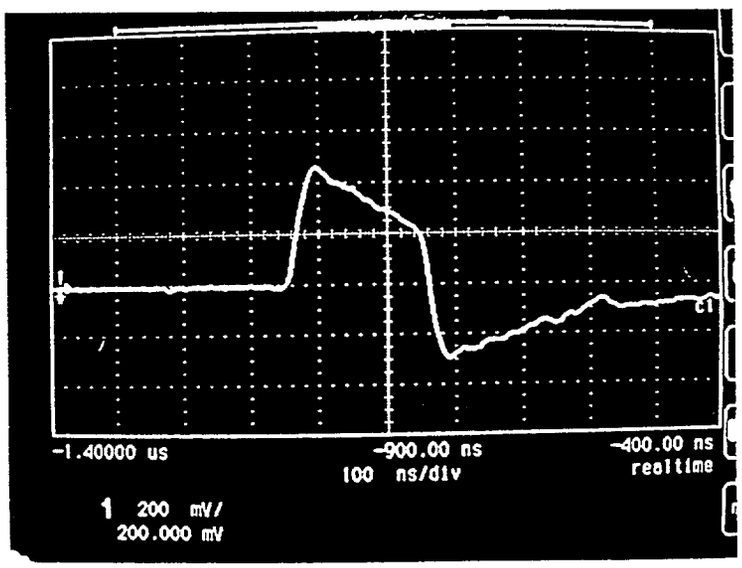

Figure 6: The primary and secondary voltage waveform when a 4M2 core and a monopolar high voltage source are used. There is a fast decay when the switch is turned on. The decay time constant is about 200 ns.

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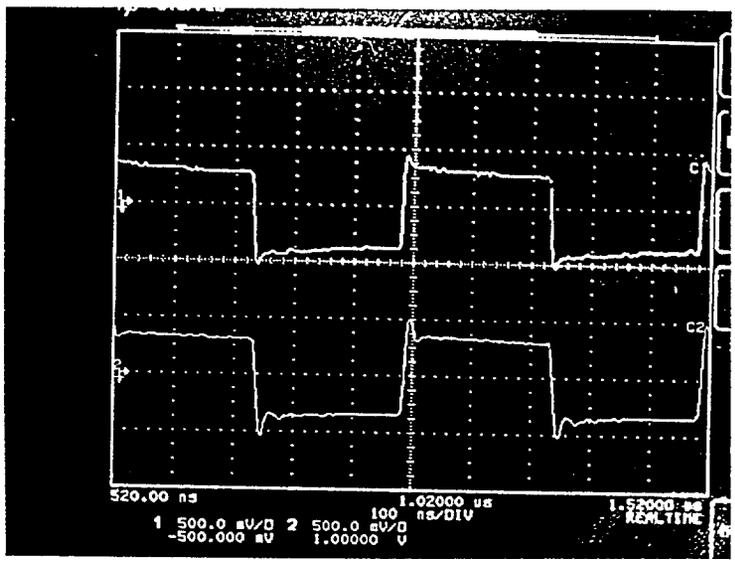

Figure 7: The primary and secondary voltage waveform when a Finemet core and a bipolar low voltage (±5 V) source are used. The rep rate is 2 MHz. The primary has a 50 Ω terminator.

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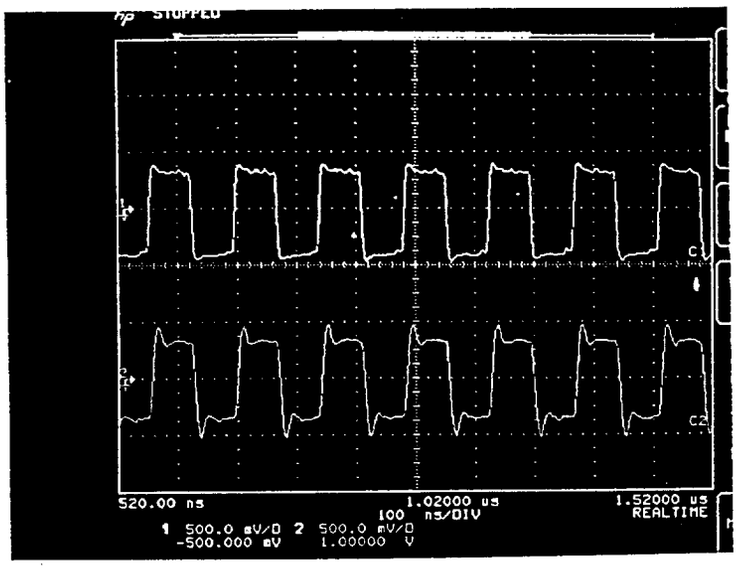

Figure 8: The same as in Fig. 7, except that the rep rate is 7 MHz.

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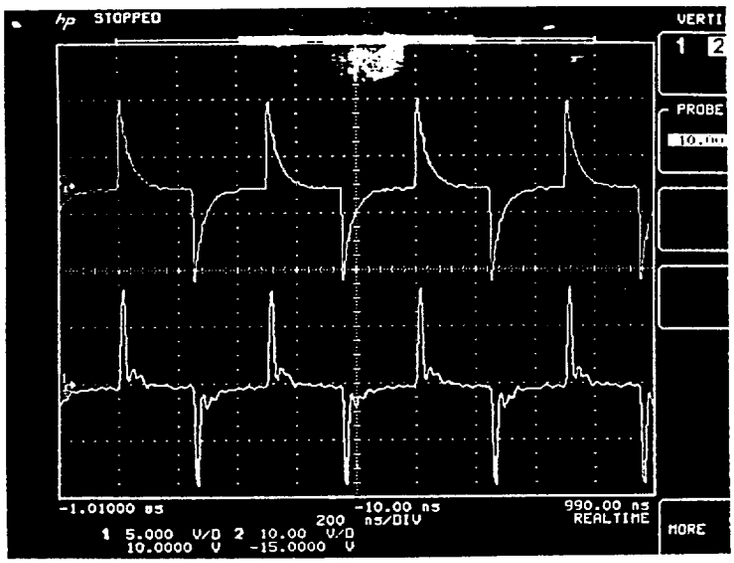

Figure 9: The primary and secondary voltage waveform when a 4M2 core and a monopolar low voltage source are used. The rep rate is 2 MHz. There is a fast decay after the switch is turned on, and a flyback voltage when the switch is turned off.

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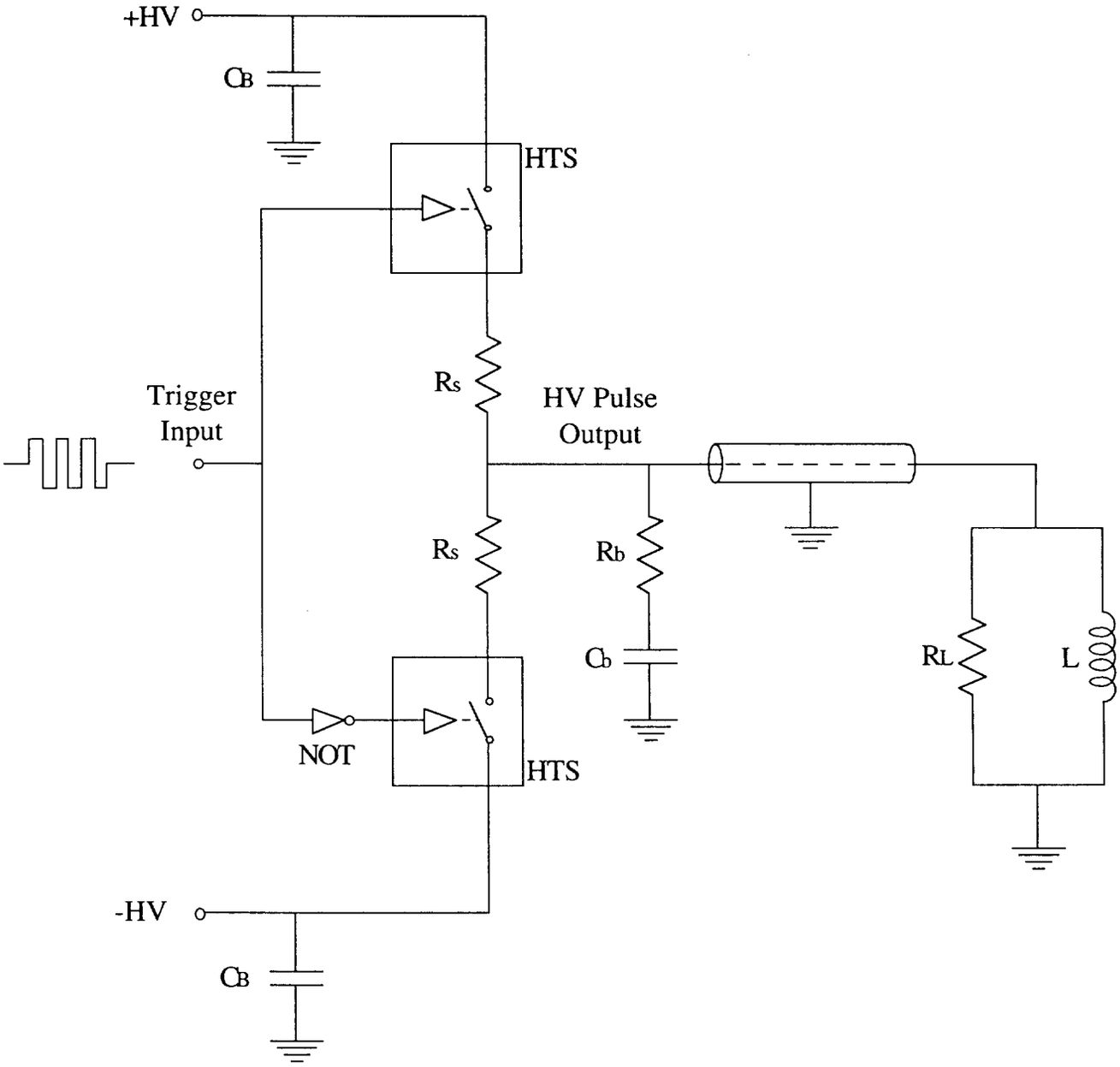

Figure 10: A circuit diagram of a bipolar (push–pull) high voltage source using two HTS transistors as the fast switchs. NOT is a polarity inverter, C_B the charging capacitor, R_s the matching impedance, R_bC_b the snubber circuit, and LR_L the inductive load.

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