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DESIGN AND TEST OF A BEAM TRANSFORMER AS A CHOPPER

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Abstract

This paper introduces a new type of chopper, which is similar to a beam transformer first discussed by R. Wideroe[1]. It is based on the fact that the RFQ has a rather small energy window. A pulsed beam transformer that provides 10% energy modulation to the beam in front of an RFQ can effectively chop the beam. It has fast rise- and fall-time and a short physical length. A prototype, which consists of a cavity and a high voltage pulsed power supply, has been constructed and tested. Two types of magnetic materials were tried for making the core of the cavity – the Finemet and the ferrite Philips 4M2. While the former gave good performance, the latter failed the test. Results from the bench measurements and a plan for beam tests are briefly described. For details the readers are referred to Ref. [2].

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, transverse deflecting, *etc.* This paper introduces a new type of chopper, which is similar to a *beam transformer* first discussed by R. Wideroe.[1] 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. 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.
   As will be seen below in our bench test, a 40 ns rise-time has been achieved with a thyratron switch. It will be shortened to 10-20 ns when a solid state switch (*e.g.*, the HTS transistor) is used.

2. Short physical length and chopping at low energy.
   The beam transformer has a length of just about 10 cm. The chopped beam is at the RFQ injection energy (which is 50 keV at the JHF).

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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 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 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. A monopolar waveform will generate significant flyback voltage on an inductive load when the power supply is switched off, and also has a large dc component.

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: +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, which 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 have high permeability μ. Two types of materials have been tested for making the core — the Finemet and the Philips 4M2 (which is a ferrite). Their magnetic parameters can be found in Ref. [3].

When a voltage waveform $v(t)$ is applied, the average field is $B_{ave} = \int v(t)dt/A$, in which A is the flux area of the core. Because the Finemet can be used at much higher B_{ave} ($\sim$ 5 kG or higher) than that for the 4M2 ($\sim$ 100 G), it makes the Finemet a preferred candidate.

The permeability of the Finemet and 4M2 has a strong dependence on the frequency. Assume the pulse has a period $\omega_0 T = 2\pi$ and a length of 2α as shown in Figure 1. The Fourier spectrum lines are $n\omega_0$, n = 0, 1, 2, ... For the JHF, $T = 500$ ns, $\omega_0 = 2\pi\times$ 2 MHz. Thus, the permeability value at 2 MHz gives a reasonable estimate. It is 2800 for the Finemet and 170 for the 4M2. This is another reason why the Finemet is a better material for a chopper.

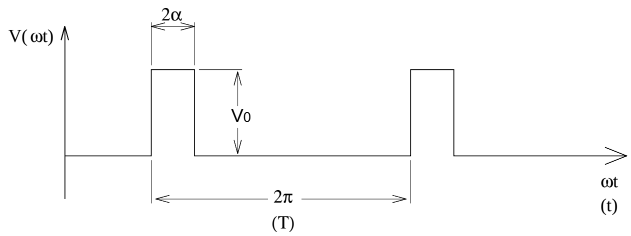

Figure 1: A series of voltage pulses with square waveform.

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). 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. The peak power of the power supply is high (hundreds of kW). But the duty factor is low. For the JHF, the duty factor is below 1%.

3 MEASUREMENTS

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 (the secondary of the transformer).

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.

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 3-4.

- Finemet:
  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. The amplitude difference between the primary and secondary voltage is small, which indicates good coupling. The maximum gap voltage reaches about 7.5 kV. The corresponding primary voltage is about 8 kV. In this test, one achieved B_{ave} = 4.9 kG and B_{max} = 6.7 kG.

- 4M2:
  In Fig. 4, 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: (1) The inductance of the 4M2 is smaller than the Finemet, the decay is faster. (2) The maximum B_{rf} of the 4M2 is rather low. At high voltage, the performance of the 4M2 is deteriorated. Moreover, when the switch is turned off, there is a voltage jump to the opposite side (flyback voltage).

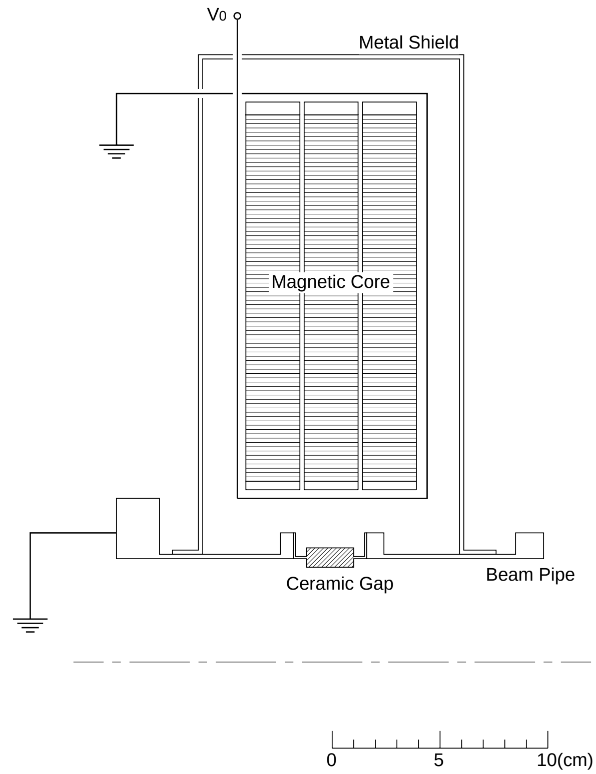

Figure 2: A test cavity used in the measurements. It consists of a magnetic core, a metal shield, a one-turn coil and a stainless steel beam pipe with a ceramic gap.

Because the thyratron rep rate is low, a separate test using low voltage high rep rate power supplies (waveform generators) was performed. The measurements were done at 2 MHz and 7 MHz. The results are similar to that shown in Figs. 3-4 and can be found in Ref. [2].

4 PLAN FOR BEAM TESTS

A new power supply and a prototype chopper have been designed and are under construction. The power supply will use two HTS 81-09 transistors for a bipolar operation, as shown in Fig. 5. 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.

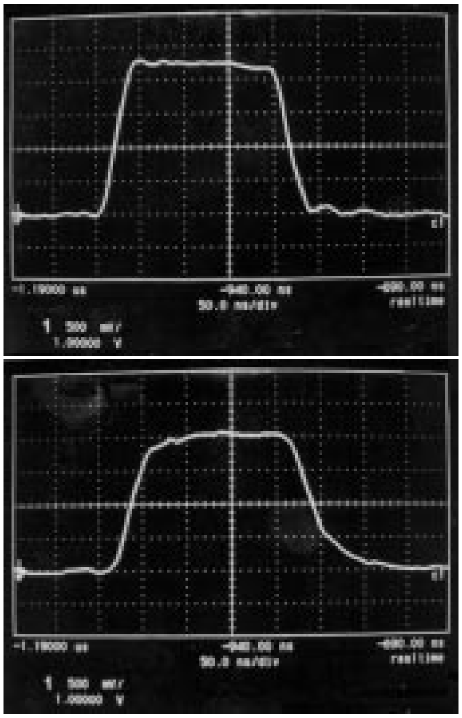

Figure 3: The primary and secondary voltage waveform when a Finemet core is used. The rise-time is about 40 ns.

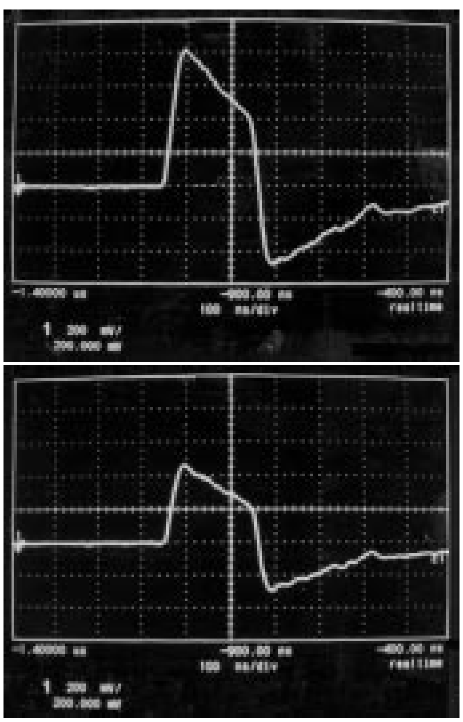

Figure 4: The primary and secondary voltage waveform when a 4M2 core is used.

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.

This chopper will be installed on the HIMAC linac for a beam chopping experiment in the fall of 1999.

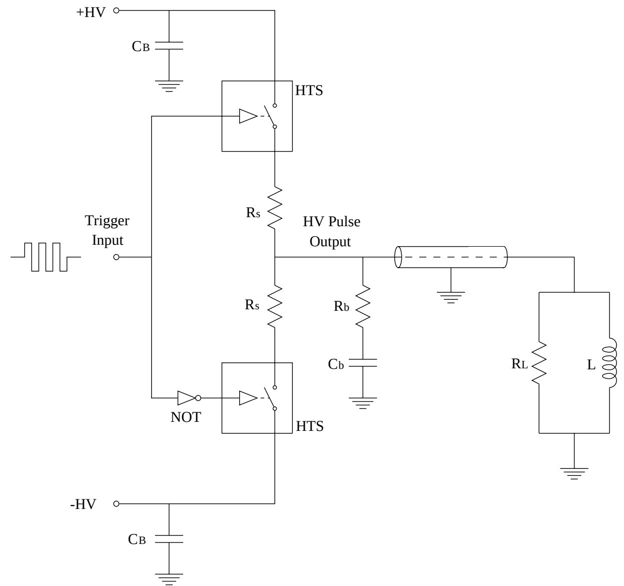

Figure 5: A circuit diagram of a bipolar (push–pull) high voltage source using two HTS transistors as the switches.

5 SUMMARY

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

The Finemet has high B_{rf} and high μ. It is a good material for the magnetic core. The 4M2 gave poor performance in the tests because its B_{rf} and μ are too low.

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

There are several issues that have not yet been addressed, including: (1) The tolerable voltage variation on top of the waveform; (2) The effect of low energy (50 keV) H^- particles bombarding the RFQ.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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[2] W. Chou *et al.*, KEK Report 98-10 (1998), and the references therein.

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