Performance of a High Voltage Power Supply Incorporating a Ceramic Transformer

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Abstract

This paper describes the performance of a high voltage power supply incorporating a ceramic transformer. Since the transformer doesn't include any magnetic material the power supply can be operated under a strong magnetic field. In the article, the efficiency of the power supply is studied against various parameters. It was found that the efficiency reaches more than 50 percent when zero-voltage switching was realized. From a 3V supply voltage, the power supply can produce 3000V at a 21 megohm load. A 5V supply voltage is enough to supply 4000V at the same load. The high voltage power supply is tested in a magnetic field of 1.5 tesla. The performance of the power supply seems almost intact in the magnetic field.

I. INTRODUCTION

This paper describes the performance of a power supply incorporating a ceramic transformer which uses the piezoelectric effect to generate high voltage. By using the ceramic transformer and an air-core coil, the power supply can produce high voltage under a strong magnetic field. The high voltage power supply described in the article is intended to produce high voltage efficiently under a strong magnetic field [1].

The output high voltage is stabilized by feedback. A feedback loop includes divider resistors, an error amplifier, a voltage controlled oscillator (VCO) and a driver circuit. An output high voltage is produced by a Cockcroft-Walton (CW) circuit. The driver circuit generates a sinusoidal carrier the frequency of which is generated by the VCO. The driver circuit drives the transformer, applying the sinusoidal carrier. The amplitude ratio of the transformer has dependence on the frequency, which is utilized by the feedback.

The transformer shows a sharp resonance in the vicinity of 120kHz. From a viewpoint of efficiency, it is favorable to drive the transformer at efficient frequencies ranging from 120kHz to 124kHz. The driver circuit includes MOS FETs and the air-core coils. The inductance of the coil and the input capacitance of the transformer composes a oscillation circuit, by which the sinusoidal carrier is produced. The inductance is adjusted so that the frequency of the oscillation can be in the efficient range. So the FETs are switched while the voltage applied to the FETs is zero. The zero-voltage switching(ZVS) of the FET was realized, which contributed to improving the efficiency.

II. CIRCUIT DESCRIPTION

The circuit of the high voltage supply is shown in Fig. 1. The high voltage supply is composed of the ceramic transformer, a cockcroft walton circuit, divider resistors, an error amplifier, a VCO and a driver circuit.

The output of the error amplifier is supplied to the VCO. Then the VCO produces a carrier wave which is frequency-modulated by the output of the error amplifier. The modulation satisfies the condition that the frequency of the carrier wave stays higher than the resonance frequency of the ceramic transformer.

The carrier wave drives the ceramic transformer through the driver circuit. Since voltage amplitude at the output of the ceramic transformer depends on the frequency of the carrier wave, the ceramic transformer converts frequency modulation at the input to amplitude modulation at the output.

The carrier wave modulated in amplitude is demodulated by rectification, and the output of the ceramic transformer is demodulated by the CW circuit. So the output from the CW circuit is the delayed and distorted output of the error amplifier. The output high voltage, which is the output of the CW circuit, is divided by the divider resistors and then fed back to the error amplifier.

The resonance shown by the ceramic transformer is sharp, and then voltage amplification of the transformer, increasing rapidly in the vicinity of the resonance frequency, depends largely on the frequency of the carrier wave. The output high voltage is stabilized by feedback, where the frequency dependence is utilized. The output high voltage is fed back to the error amplifier to be compared with a reference voltage. The voltage difference between the input of the error amplifier is amplified and fed to the VCO, which then adjusts the frequency of the carrier wave so as to reduce the voltage difference.

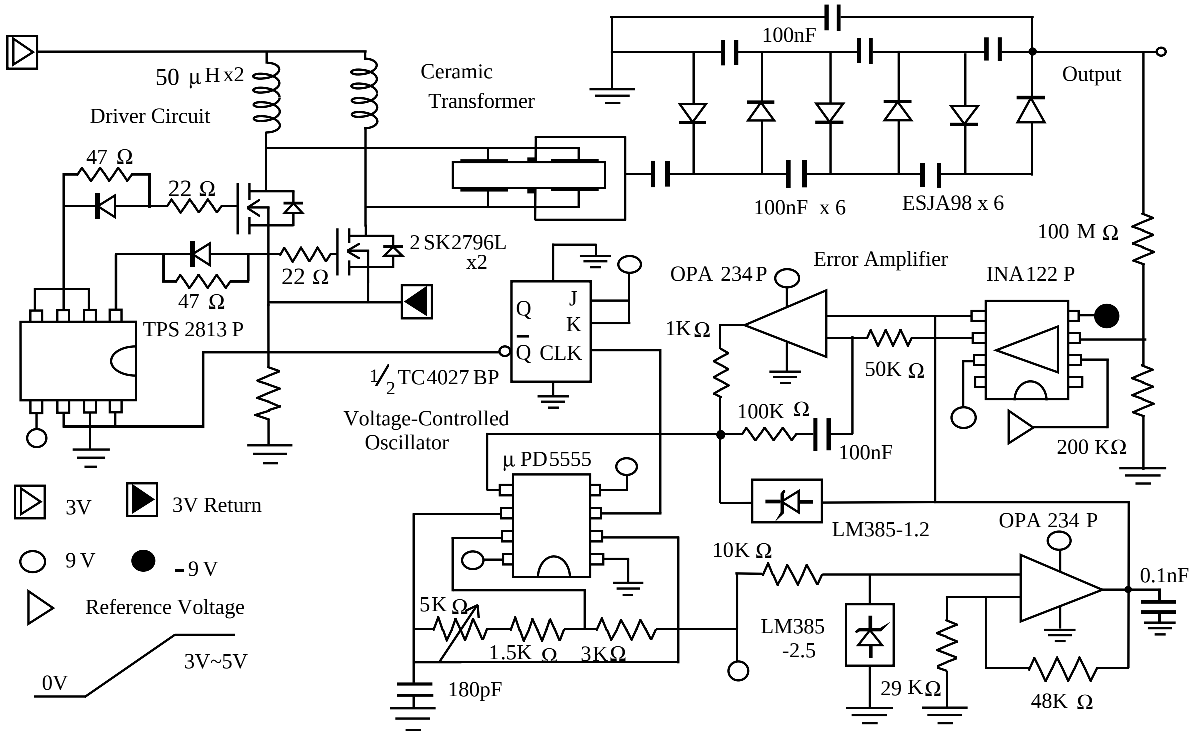

Fig. 1 Schematic circuit of the high voltage power supply, where an error amplifier is implemented by INA122 and OPA234 and a voltage controlled oscillator by μPD5555 and TC4027.

which eliminates the power consumed by a damped capacitance mainly due to the ceramic transformer. The driver circuit includes two identical resonant circuits as shown in Fig. 1, each of which is composed of a MOS FET and a inductor(implemented by an air-core coil). The FETs are simultaneously switched on and off alternately by the output of the VCO. The inductance in the resonant circuit resonates with the damped capacitance of the ceramic transformer while the FET is turned off, and the inductor stores the current while the FET is turned on. One resonant circuit makes a half sinusoidal wave whose amplitude is about 3 times of the voltage supplied to the resonant circuit. The other resonant circuit makes the other half sinusoidal wave alternatively. Thus the resonant circuit generates a quasi-sinusoidal carrier wave at the input terminals of the ceramic transformer. The FETs are switched over while the voltage applied between the input terminals stays almost zero volt.

III. PERFORMANCE OF HIGH VOLTAGE POWER SUPPLY WITH CERAMIC TRANSFORMER

The high voltage supply is implemented on a printed board as shown in Fig 2.

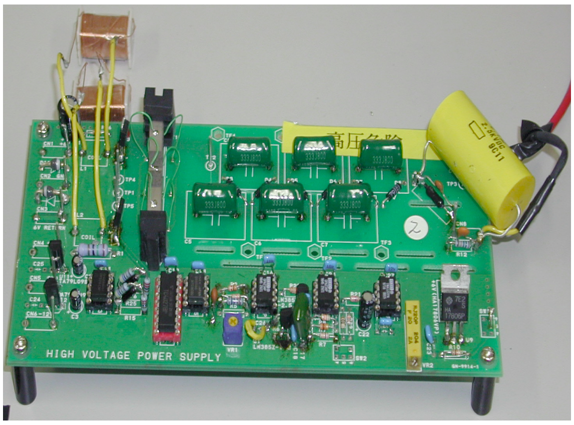

Fig. 2 A picture of the high voltage power supply described in the article.

A. Inductance Dependence on Efficiency

In order to improve the efficiency, it is important to realize the ZVS at the driver circuit. So the range of the frequency where the ZVS is realized is studied in the relation with the inductance of the two air-core coils in the driver circuit. The ZVS is realized at lower frequencies than the frequency of the resonance at the driver circuit. The frequency of the resonance at the driver circuit largely depends on the inductance. The performance of the power supply is measured at inductances of 40μH, 50μH, 65μH, 80μH and 100μH. Efficiency is analyzed form a viewpoint of the ZVS and its dependence on the frequency of the

VCO.

In Fig. 3 and 4, the output high voltage versus the VCO frequency, the efficiency versus the VCO frequency, and the efficiency versus the output high voltage are plotted for each inductance, where the efficiency is a ratio of the power consumption by a 21 megohm load to the power supplied to the driver circuit. The efficiency increases as the frequency come close to the resonance frequency of about 120kHz and reaches the almost constant value of more than 50 %.

Fig. 5 and 6 show the output voltage of each single FET. Fig. 7 and 8 show the quasi-sinusoidal wave which are the voltage difference between the output of two FETs. The quasi-sinusoidal wave is applied to the transformer. Where the efficiency is more than 50 %, the quasi-sinusoidal wave is nearly a ideal sinusoidal wave and ZVS is realized as shown in Fig. 6 and 8.

When the frequency is not in the efficient range, the efficiency is low and the ZVS isn’t realized as shown in Fig. 5 and 7. The voltage range of efficient high voltage generation is dependent of the inductance. As for the efficiency versus output high voltage, it can be seen that the plateau of efficiency is wider for a smaller inductance, and that a larger inductance reaches a higher plateau in efficiency. So it seems important not to select such the inductance that locates the frequency of resonance at the driver circuit close to the resonance frequency of the transformer. Placing the frequency of resonance at the driver circuit in the efficient range of the frequency contributes to improving the efficiency of the power supply.

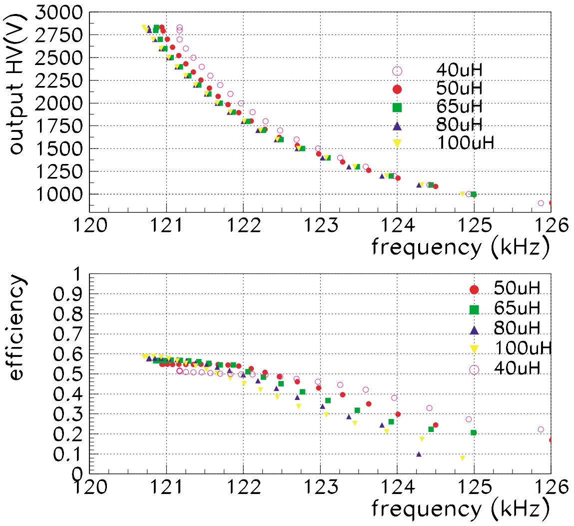

Fig. 3 Dependence of the output high voltage and of the efficiency on the VCO frequency are shown for each inductance : the supply voltage to the driver circuit is 3V and 2SK2796L is employed.

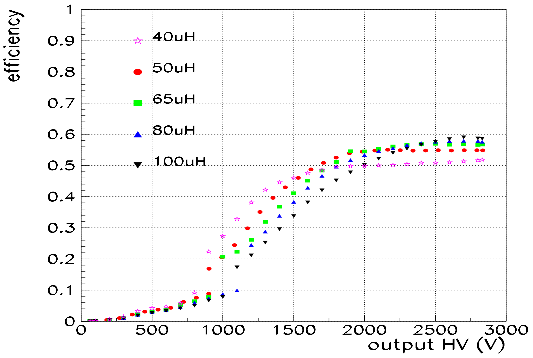

Fig. 4 Dependence of the efficiency on the output high voltage is shown for each inductance.

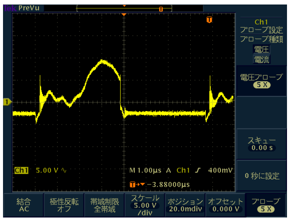

Fig. 5 900V, 130.1kHz

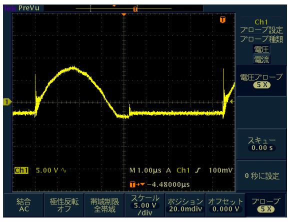

Fig. 6 2550V, 121.2kHz

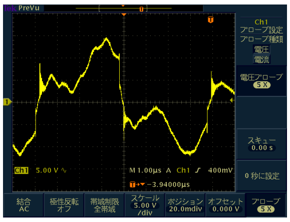

Fig. 7 900V, 130.1kHz

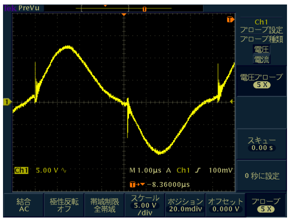

Fig. 8 2550V, 121.2kHz

B. Dependence of MOS-FET on Efficiency

The MOS-FET used in the driver circuit is also important for efficiency. Low power MOS-FETs with various on-resistance were selected and tested. Specifications of the selected MOS-FETs are summarized in the Table 1. In Fig. 9 (a), the efficiency versus output high voltage are shown for selected MOS-FETs. In Fig. 9 (b), maximum output high voltage versus the supply voltage to the driver circuit are plotted.

	Drain-Source on-Resi.(ohm)	input C.(pF)	Turn-on Delay-time(ns)
2SK1151	3.5	160	5
2SK2796L	0.12	180	9
2SK2933	0.040	500	10
2SK2939	0.020	1100	15

Table 1
Typical specifications of the MOS-FETs

MOS-FET 2SK1151 with an on-resistance of 3.5 ohm is worse in both the maximum output high voltage and the efficiency than others with lower on-resistance. The on-resistance of the MOS-FET should be low for efficiency. Yet the capacitance in the MOS-FET with lower on-resistance tends to be larger. A large input capacitance of the MOS-FET may causes considerable power consumption. The large capacitance leads to long delays which are unsuitable for the ZVS. Therefore, we selected 2SK2796L to be used in the power supply.

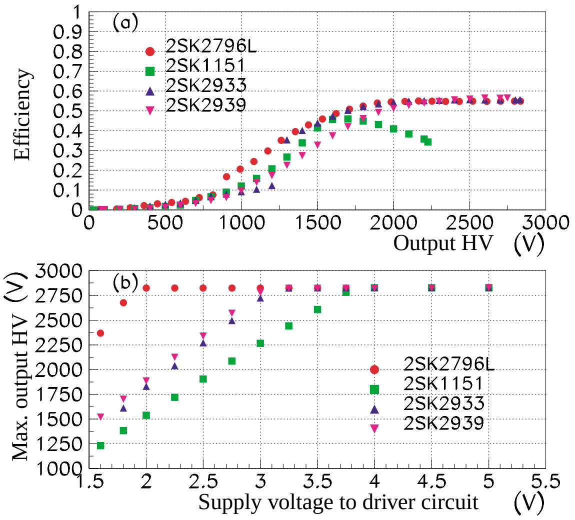

Fig. 9 (a): Efficiency vs. output high voltage plot for each FET.; (b): Plot of maximum output high voltage for each FET.

C. Supply Voltage Effect on Efficiency and on maximum Output Voltage

The supply voltage to the driver circuit is raised to the output high voltage. The high voltage power supply generates the high voltage power supply efficiently from a low supply voltage. Efficiency is investigated from a viewpoint of the dependence on the supply voltage. Fig. 10 and 11 provide the plots of the efficiency versus the output high voltage for each supply voltage, where 2SK2796L is employed in the driver circuit. As seen from Fig. 10, a 2V supply voltage can produce the output high voltage close to 2800V with high efficiency. From Fig. 9(b), a 1.6V supply voltage can generate the output high voltage close to 2400V.

The amplitude of the sinusoidal carrier is about three times the supply voltage to the driver circuit. The output voltage of the transformer is furthermore multiplied by about six times in the CW circuit. When the supply voltage to the driver circuit is 2V, the maximum output high voltage reaches 2700V at a load of 21 megohm. It can be seen that the amplitude ratio of the transformer reaches more than eighty around the resonance. This means a 5V supply voltage to the driver circuit is large enough to produce a 4000V output high voltage.

D. Dependence of Capacitance in CW Circuit

Capacitors with several values were tested in CW circuit, and its effect on efficiency was studied. Capacitors of 220μF, 100μF, 33μF and 12μF were employed for test. We checked the noise level and the efficiency for each capacitor, plotting the efficiency versus the output high voltage as shown in Fig. 12. It can be seen that efficiency does not depend on the capacitance. A capacitor of smaller capacitance will works in the CW circuit.

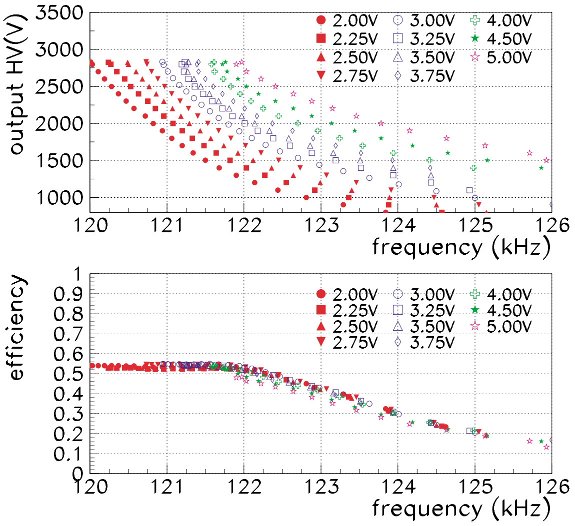

Fig. 10 Output high voltage and efficiency are plotted for each supply voltage against VCO frequency.

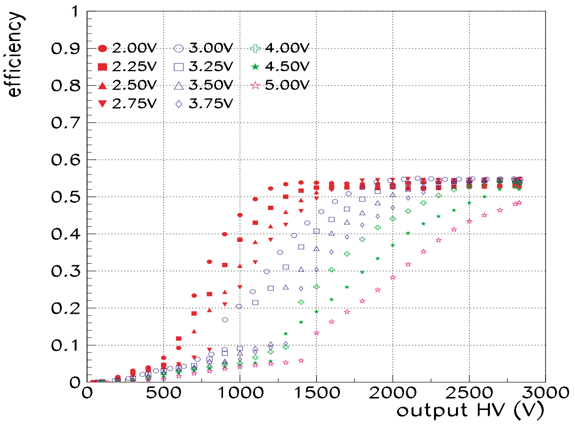

Fig. 11 Efficiency vs. output high voltage plot for each supply voltage.

E. Static and Dynamic Stability

Static and dynamic responses of the power supply were measured. Fig. 13 shows the setup of the response measurement. A mercuric switch was employed to implement instant change of load in magnitude such as changing from 21 megohm to zero megohm and from zero megohm to 21 megohm. The change of the load causes a transient response at the output high voltage.

Stability of the power supply were estimated by measuring transient responses at the output high voltage. The transient responses at the output high voltage are shown in Fig. 14. The power supply described in the article shows quick feedback. The static response at the

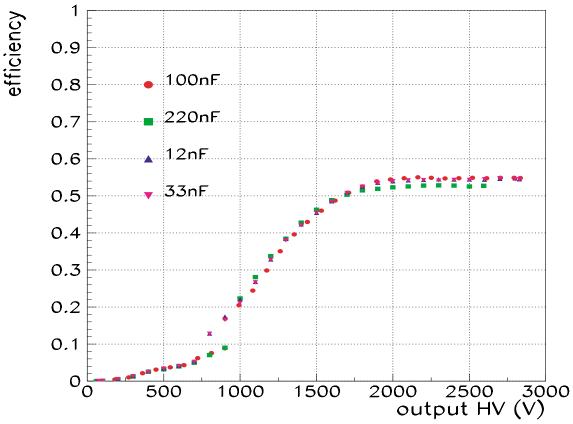

Fig. 12 Efficiency vs. output high voltage plot

output high voltage is the voltage shift. The voltage shifts were measured by using high voltage probe. The voltage shift for the load change is within 100mV when the output high voltage is 2000V. The noise level triggering by the auto-trigger mode of a digital scope is shown on Fig. 15. When the output high voltage is 2000V, it can be seen that the noise is about 20 mV at the peak. The sinusoidal component of the trace in Fig. 15 is same in frequency with the carrier wave.

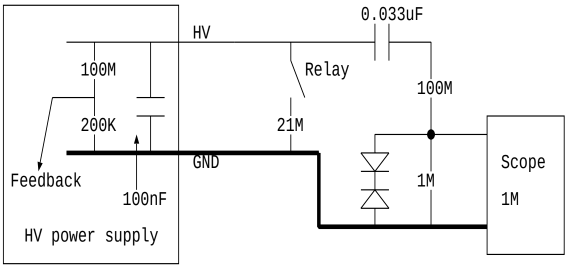

Fig. 13 Setup of the response measurement

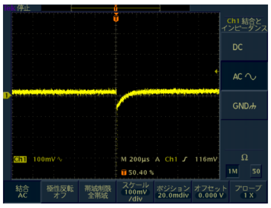

Fig. 14 Transient response on changing the load from zero to 21 megohm.

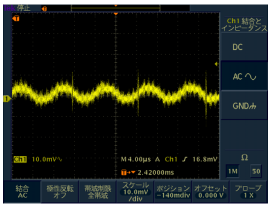

Fig. 15 Trace of noises by a auto-trigger mode

F. Test in a Magnetic Field of 1.5 Tesla

Efficiency in a magnetic field of 1.5 tesla was tested at the facilities in KEK. Fig. 16 shows the plots of efficiency with and without the magnetic field. There might be subtle difference between the plots, which remains to be studied.

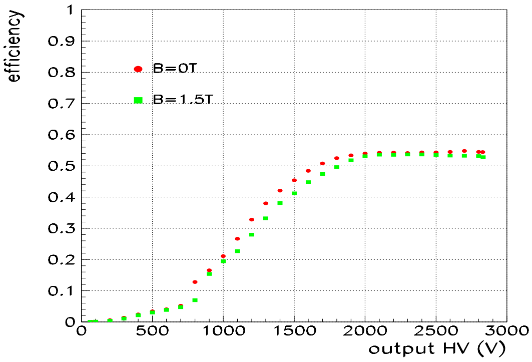

Fig. 16 Effect of magnetic field on dependence of efficiency against output high voltage

IV. ACKNOWLEDGMENTS

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V. REFERENCES

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