DEVELOPMENT OF A HIGH-PERFORMANCE CAPACITIVE DIVIDER USING CERAMICS FOR PULSED HIGH-VOLTAGE MONITORING

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Abstract

We have developed a new capacitive-voltage-divider (CVD) using an Al_2O_3 ceramic dielectric for pulsed high-voltage monitoring, to be used for example in monitoring waveforms for a high power klystron (350-kV and 4.5-μs). To reduce the temperature dependence of the voltage divider, we have chosen ceramic dielectric materials that can provide a small thermal expansion coefficient. We investigated the high-voltage breakdown thresholds of several alumina-ceramic disks using a test-bench of our own design. A high-power test on one of the prototype CVDs was done and we obtained an accurate and highly faithful monitoring signal. The divider was successfully used to monitor a 367-kV peak voltage, 4.5-μsec pulse width, 50-pps repetition rate waveform. The maximum test voltage was limited by the modulator capabilities, not breakdown of the CVD.

INTRODUCTION

Klystrons are a key component in linear accelerators, especially for an e^+e^- collider [2]. In developing high performance klystrons, obtaining accurate information about the voltage applied to the klystron cathode is very important. We usually use commercial CVD monitor such as the one shown in Fig. 1 to monitor pulsed high voltages as high as 350-kV. This one has a HV electrode supported by acrylic resin and a sensor electrode inside a guard-ring [3].

The electrodes immersed in insulation oil form a capacitor. Although this type divider can be well designed and has been used for many years, there are still some outstanding issues such as the following:
(1) The acrylic support has a large thermal expansion coefficient and is weak under mechanical stress. Thus the HV electrode is sometimes squashed during transportation or in setting up the klystron, and can even be broken by thermal shocks due to sudden changes in its surroundings or by vibration induced by the transformer. (2) The capacitance is sensitive to the condition of the insulating oil, and so it changes with changes in the temperature or the quality of the oil.

Figure 1: Conventional capacitive-divider used in the KEKB klystron oil tank (Stangenes CVD-350)

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These causes result in changes to the dividing ratio, and thus data from these dividers is not reliable and reproducible. Therefore we undertook to develop a very stable high-performance CVD. We began the R&D by looking at the available dielectric materials for the HV-capacitor.

In this paper, we will present the detailed design and results of a high power test on the new CVD.

DESIGN

The goals of the R&D were to produce a monitor for 10-μs, 400-kV input pulses which could achieve the following: (1) Division ratio of 1/5000-1/10000, (2) Robust construction, (3) The division ratio should be insensitive to environmental conditions and be stable over time, (4) Mass productivity is essential.

Materials Research

Requirements for any dielectric materials to be used in the HV-capacitor are (1) high dielectric breakdown threshold, (2) mechanical and electrical insensitivity to thermal change, (3) high dielectric constant and (4) reliable commercial supply at low cost. After researching the market, two kinds of Al_2O_3 fine ceramic materials of different purities were selected as candidate for the HV-capacitor, as shown in Table 1.

Table 1: Material Comparison.

	Insulation oil	Al_2O_3 ceramic	
		General	Fine, High-Purity
Density (g/cm^3):	0.87 - 0.98	3.7 - 3.9	3.9 - 4.0
HV breakdown Threshold (kV/mm):	30 - 40	10 – 15	15 - 20 (75*)
Dielectric const. (ε_r):	2.2	8 – 10	
Thermal expansion coefficient. (10^{-6}/K):	850	7 – 8	2

*This data point was measured using our own test-bench and methods.

There are commercially available ceramic capacitors with metallized electrodes good for use up to a few kilo-volts, and we could use their design and construction techniques as a starting point for the development of 400-kV class pulsed voltage capacitive-dividers.

These ceramic dielectric materials had already been tested to find their high-voltage breakdown threshold using a test-bench of our own design [4]. This test-bench was designed to measure the high-voltage threshold under an applied DC-voltage of 0 to -150-kV in degassed insulation oil. With it, we can test metallized electrode ceramic disks of various sample materials. Since vapor or micro-bubbles are removed by pumping down to 10^{-1} Torr, we can investigate more intrinsic breakdown voltage characteristics of test sample materials under standardized benign environmental conditions. Furthermore, this environment is the same one that is found in klystron oil tanks, and thus the test bench result gives data directly applicable for the proposed application of the new capacitive-divider. With this test-bench we obtained a high-voltage breakdown threshold of 75-kV/mm for one ceramic (see Table 1), and the CVD design was based on this value.

Design Concept and Fabrication

From the result of the high-voltage threshold test, the thickness of the HV ceramic capacitor was set to be 20-mm for operation up to 400-kV. For testing purposes, we made samples with two differently shaped dielectrics and two different types of electrodes. Fig. 2 shows the case where both the electrodes are formed from a 15-μm metallization layer of Mo-Mn. In the cup structure on the left of Fig. 2, the electrode disk was surrounded by a metallized annulus with a 2-mm gap separation; the outer ring is connected to ground potential. Since the ground plane protects the sensor electrode from discharge or outer fields, the signal line is a bit safer even if breakdown should occur in the transformer tank.

For the second electrode type, we used an adhesive to bond metal preformed electrodes to the ceramic dielectric as shown in Fig. 3. We used the EMSYS code to optimize the physical shapes of the ceramic, and checked the electrical field distributions for the various structures. Fig. 4 shows an electrical field distribution for a cup type CVD.

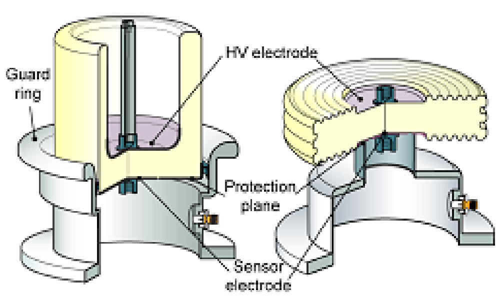

Figure 2: Cutaway drawing of the CVD monitor.

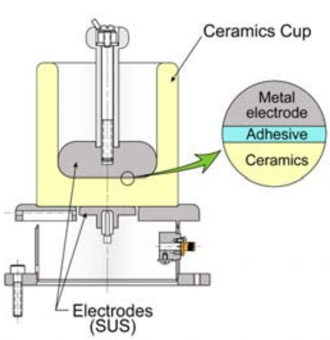

Figure 3: Cup type divider with adhesive bonded preformed electrodes.

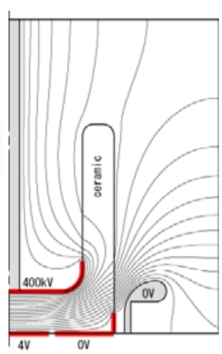

Figure 4: Simulation of the electric field for the cup type divider with corona ring.

The accuracy of the monitored voltage is controlled by the division ratio and its stability, and is thus not determined only by the HV ceramic capacitor alone, but by the entire circuit, and final voltage calibration can be done on the low voltage side. (See *An Equivalent Circuit*) If we design the CVD capacitor to be stable, it can be relatively insensitive to the mechanical dimensions and thus the production tolerances for the HV-capacitors can be loosened, reducing machining cost.

The various combinations of ceramic materials, shapes and electrode types for the dividers have already been made up and tested; their specifications are listed in Table 2. The important features of each type are as follows:

Cup type: Flashover is rather more unlikely to occur because the path between electrodes is shielded by the ceramic out to where the electric field is weaker. Moreover, the guard-ring protects against breakdown at outer edge of ground plane. However, it more costly than the disk type divider.

Disk type: This type has good mass productivity, and can be stacked to create dividers for even higher voltages. The ceramic is grooved to obtain longer surface distance separations because the electric field at the metallized edge is strong.

Table 2: Characteristics of dividers.

	CVD-350 1)	Cup type	Disk type
Material	Insulation oil	Al_2O_3 ceramics	
Dividing ratio: Accuracy (%):	1/5000 -1/25000 5	1/5000 < 1 2)	
Total capacitance (pF):	15	31 2)	16 2)
Sensor capacitance (pF):	(Unknown)	5	2
Pulse droop (%/μsec):	0.01 4)	< 1 3)	
Flashover distance (mm):	225	165.7	200
Size (Ø×H): (mm):	165.1× 247.65	150×200	135×150

1) Stangenes CVD-350. 2) From simulation. 3) Design target value. 4) With 1 MΩ cable.

An Equivalent Circuit

Fig. 5 gives a schematic of the complete CVD monitor circuit. The capacitance C_1 is that of the capacitor under development here - which is concentrated between the two electrodes separated by the ceramic. The capacitance C_2 was adjusted to give a dividing ratio of for example 1/5000. A picture of the new developed disk type CVD mounted in the transformer tank is shown in Fig. 6.

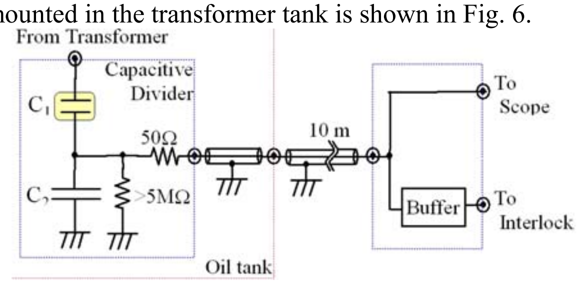

Figure 5: An equivalent circuit for the complete CVD monitor.

HIGH POWER TEST

Under test, one of the new disk type capacitive dividers, with metallized electrodes provided a very high fidelity signal waveform as may be seen in Fig. 7, and we had great hopes for it. Unfortunately, the divider suffered a destructive breakdown when the 4.5-μsec, 50-pps repetition rate test voltage was raised to 229 kV.

The breakdown started near the metallization edge (see Fig. 8), and by careful observation we could see many small corona tracks at the edges of both the HV electrode and the protection metallization.

Figure 6: A disk type CVD mounted in a klystron oil tank.

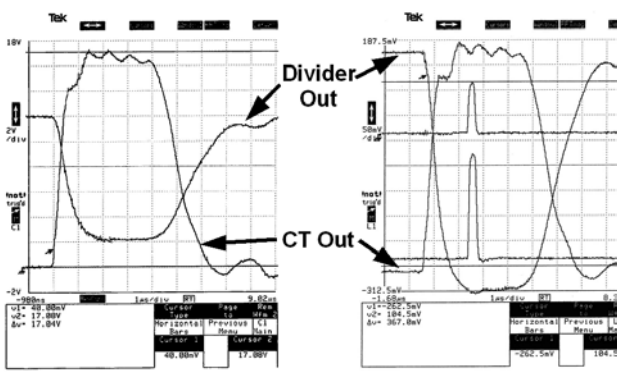

Figure 7: Recorded pulse through dividers. Left: disk type at 229.2 kV, right: Stangenes CDV-350 at 237.8 kV. A faithful pulse waveform was obtained with the new divider. Right: 367-kV, 4.5-μsec high voltage waveform.

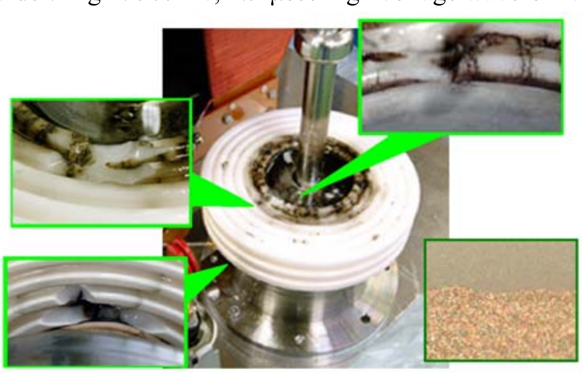

Figure 8: Divider destroyed by breakdown. There was no damage to the transformer or anything else, even the low voltage divider capacitor. Many tracks can be seen around the metallized edge where the discharge occurred. A microphotograph of the metallized edge is inset at the bottom right.

After attempts with various methods for Mo-Mn metallization, we eventually abandoned trying to make the electrodes have the smoother edges which might have solved the problem.

One of the cup shaped CVDs, one with the adhesive bonded preformed electrodes was successfully used to monitor tests with voltages up to 367-kV, using the same 4.5-μsec pulse width, 50-pps repetition rate (Fig. 9). It is thought that the main contributing factor for the improvement is the very smooth round edge of the electrodes. In the end, the maximum voltage that could be applied to test the divider was limited by the modulator output capabilities.

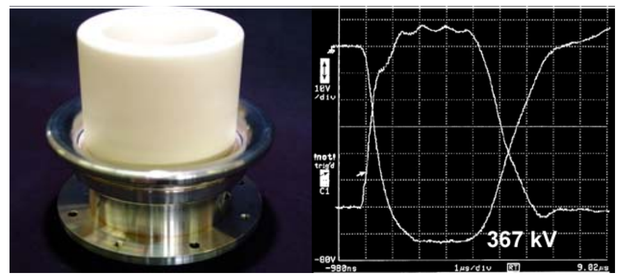

Figure 9: Ceramic high-voltage monitor. Left: Cup type monitor.

SUMMARY

We have developed a very stable and accurate high-voltage monitor, to be used for monitoring klystron pulse voltages. Two different types of CVDs were shown to provide very high fidelity output signal waveforms. Since the CVD dielectric material is a ceramic, the monitoring capacitance division ratio can be kept quite stable even under ambient temperature changes, or changes to the set-up configuration, or against mechanical stresses applied to the monitor port through the input lead.

REFERENCES

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