JAERI-M
93-214

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October 1993

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編集兼発行　日本原子力研究所
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Development of an Amorphous Surge Blocker for a High Voltage Acceleration Power Supply of the Neutral Beam Injectors

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(Received October 1, 1993)

An amorphous surge blocker for a high voltage acceleration power supply for the neutral beam injectors has been developed. Since the saturation magnetic flux density of the amorphous core is higher than that of the ferrite core, the surge blocker made of amorphous cores can be reduced in size appreciably compared to the conventional ferrite surge blocker. A 350 kV, 0.05 volt-second amorphous surge blocker was designed, fabricated and tested. The amorphous core was made by winding an amorphous tape with a film for the layer insulation and was heat-treated to recover the magnetic characteristics. The core is molded by epoxy resin and installed in a FRP insulator tube filled with SF_6 gas for the insulation. The volt-second measured was higher than the designed value and the electrical breakdown along the cores and between layers was not observed. This test result shows that the amorphous surge blocker is applicable for a dc acceleration power supply for high energy neutral beam injectors.

Keywords: Surge Blocker, Neutral Beam Injector, Amorphous, Ferrite, Volt-second

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中性粒子入射装置高電圧加速電源用アモルファスサージブロッカーの開発

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（1993年10月1日受理）

中性粒子入射装置高電圧加速電源用のアモルファスサージブロッカーの開発を行った。アモルファスコアの飽和磁束密度がフェライトコアに比較して高いため，アモルファスコアを用いて構成したサージブロッカーは従来のフェライトコアを用いたサージブロッカーに比べ大幅に小型化が可能である。そこで，350 kV，0.05 Volt-second のサージブロッカーの設計，製作，試験を行った。アモルファスコアはアモルファスの薄帯を層間絶縁用のフィルムとともに巻き上げることにより成形し，磁気特性を回復させるための熱処理を施した。コアは電気絶縁のためエポキシ樹脂でモールドし，SF_6 ガスを充填したFRP管に収納した。試験の結果，設計値以上の Volt-second 値を有することが確認された。また，コアでの絶縁破壊は観測されなかった。これより，アモルファスサージブロッカーが中性粒子入射装置高電圧加速電源に適用可能なことが明らかとなった。

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1. Introduction

Acceleration electrodes in the ion source for a neutral beam injector (NBI) suffer from frequent electrical breakdowns. When the breakdown occurs, the high voltage output of the power supply for the beam acceleration is cut off by a series switch like tetrodes or GTO thyristors. However, the energy stored in the stray capacity of the high voltage transmission line and the insulating transformer for source power supplies is dissipated in the electrodes. This causes the local melt of the electrodes and hence the deterioration of the voltage holding. Various counter-measures have been tried so far to protect the electrodes [1],[2],[3]. For example, a surge blocker (SB) is adopted in the neutral beam injector for JT-60 [4]. It is composed of a magnetic material and is installed between the power supply system and the ion source. It works as a high impedance for breakdowns which restricts the short circuit current and absorbs the energy. In positive-ion-based neutral beam injectors, in which the beam energy is below 200 keV, ferrite cores were utilized as a magnetic material.

On the other hand, the surge blocker using ferrite cores becomes large in a negative-ion-based neutral beam injector because the stored energy increases due to high beam energy of 500-1300 keV. Furthermore, the radius of ferrite cores is restricted from the manufacturing view point. To reduce the size, the surge blocker using amorphous material, which has higher saturation magnetic flux density than ferrite, has been investigated.

In this paper, the design, the fabrication and the test of a 350 kV amorphous surge blocker are described.

2.Design of the amorphous surge blocker

A schematic diagram of the surge blocker application is shown in fig.1. The output of the power supply is connected with the ion source through the surge blocker. A resistor is equipped in the secondary circuit of the surge blocker to suppress the surge current. A bias power supply is used to cancel the load current and to move the core magnetically to the position (a) in a typical B-H curve shown in fig.2. The equivalent circuit is shown in fig.3. The surge blocker works as a reactor L_B with a parallel resistor R_B when the breakdown occurs. The values of L_B and R_B are decided to restrict the current and the energy dissipated in the electrodes to acceptable values.

One of the important parameter of the surge blocker is volt-second. This is the product of the voltage applied to the surge blocker and the applied time. This value have to be large so that the cores may not saturate magnetically. Volt-second depends on the material and the core shape. Namely, volt-second is given by the product of the magnetic flux density and the cross section area. In the design of the surge blocker, the selection of the magnetic material affects the total system design of the high energy neural beam injectors, since the surge blocker becomes enormous.

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Amorphous alloy, which is used as a high frequency magnetic material, has higher saturation magnetic flux density than ferrite. Typical values are 1.56 T for the amorphous alloy and 0.38 T for the ferrite. Furthermore, the amorphous core with a large diameter can be manufactured, since the amorphous core is made by winding the amorphous tape. Thus, the amorphous alloy is attractive as a material for the surge blocker.

A 350 kV, 0.05 volt-second surge blocker, which could be used in the 350 kV ion source test stand, was designed for two cases; the amorphous core and ferrite core. Table 1 shows the design values. Since the amorphous tape is conductive, the core requires the layer insulation. This reduces the space factor. However, the length of the amorphous surge blocker is still about half of the ferrite surge blocker. This is very advantageous for the high voltage system.

On the other hand, winding of the amorphous tape to the core degrades the magnetic characteristics. Namely, the effective saturation magnetic flux density may decrease. This may increase the required length of the core. Therefore, the heat treatment is usually required after the winding. To confirm the magnetic characteristics of the amorphous alloy in the form of the core and the soundness of the insulation of the core, a 350 kV amorphous surge blocker was fabricated.

3. Fabrication of a 350 kV amorphous surge blocker

At first, a model core, which has the inner diameter of 81 mm, the outer diameter of 143 mm and the length of 105 mm, was material, has higher saturation magnetic flux density than ferrite. Typical values are 1.56 T for the amorphous alloy and 0.38 T for the ferrite. Furthermore, the amorphous core with a large diameter can be manufactured, since the amorphous core is made by winding the amorphous tape. Thus, the amorphous alloy is attractive as a material for the surge blocker.

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At first, a model core, which has the inner diameter of 81 mm, the outer diameter of 143 mm and the length of 105 mm, was fabricated and tested. The amorphous tape is 25 micrometers thick and the insulation film is also 25 micrometer thick. The result was not satisfactory. After the heat treatment, the space factor of the core decreased to 32.3 % and the effective saturation magnetic flux density was 1.1 T. This means that the length of the surge blocker becomes 1.76 m and is longer than the ferrite surge blocker. The reason of the degradation of the core was supposed to be the distortion of the core caused by the heat treatment. To reduce the distortion, the insulation film was changed to the film of 7.5 micrometers thick. The new core had the space factor of 65.7 % and the effective saturation magnetic flux density of 1.45 T after the heat treatment. This means that the length of the surge blocker can be reduced to 0.66 m.

On the basis of the test results of the new model core, full-scale cores were fabricated. The core has the inner diameter of 140 mm, the outer diameter of 300 mm and the length of 105 mm. The core is molded by epoxy resin for insulation. The test of a unit core showed that the effective saturation magnetic flux density was reduced by 10 % compared to the model core. This was supposed that the distortion of the core was increased by increasing the core size. The number of the cores was determined to be eight with a margin. Eight cores are installed in the FRP insulator tube filled with SF_6 gas of 3.0 kgf/cm^{2}G. The reactor for the protection of the bias power supply is also installed inside the insulator tube. The surge blocker is insulated from the ground by the insulators. Figure 4 shows the structure of the 350 kV amorphous surge blocker.

4.Test result

The surge blocker was tested by the test circuit shown in fig. 5 to confirm the voltage holding of the cores and to measure the volt-second. The impulse voltage was below 385 kV. The rise time of the output of the impulse generator was long and insufficient for the test. A spark gap was connected in series to make the impulse waveform steep. Figure 6 shows the waveforms of voltage applied to the surge blocker and current. Figure 6 (a) corresponds to the case in which the bias current is not applied before the impulse. Figure 6 (b) corresponds to the case in which the bias current is applied in the opposite direction with the impulse current before the impulse. The volt-second values were estimated by integrate the first half wave of the voltage waveforms. They were 0.04 volt-second for figure 6 (a) and 0.074 volt-second for figure 6 (b). These values correspond to the magnetic flux density Bs-Br and Bs+Br, respectively, as shown in fig.2. Therefore, the volt-second of the surge blocker, which is given by the average of two values, is 0.057 volt-second. Current waveforms have peaks when the voltage becomes almost zero. Namely, the surge current is suppressed until the cores are saturated. The total length of cores is 0.84 m and is about a half of the ferrite cores.

Furthermore, the breakdown along the cores and between layers was not observed.

5.Conclusion

The 350 kV amorphous surge blocker was fabricated and tested. It was shown that the amorphous surge blocker could be reduced to about a half of the ferrite cores in size. The soundness of the insulation of cores was also confirmed. These results shows that amorphous material is applicable for the surge blocker.

The improvement of the procedure of the winding and heat treatment and the reduction of the thickness of the insulator will lead to the further improvements of the amorphous surge blocker.

Acknowledgment

The authors would like to thank other members of the NBI Heating Laboratory for their valuable discussions. They would also like to express their gratitude to Dr. Y. Tanaka, Dr. S. Shimamoto and Dr. N. Shikazono for their continuous support and encouragement.

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Table 1 Comparison of the 350 kV, 0.05 volt-second surge blockers made of the amorphous cores and the ferrite cores

Material	Amorphous	Ferrite
Inner diameter(m)	0.14	0.14
Outer Diameter(m)	0.3	0.3
Space factor (%)	50	100
Volt-sec	0.05	0.05
Flux density (T)	1.56	0.38
Length (m)	0.8	1.64

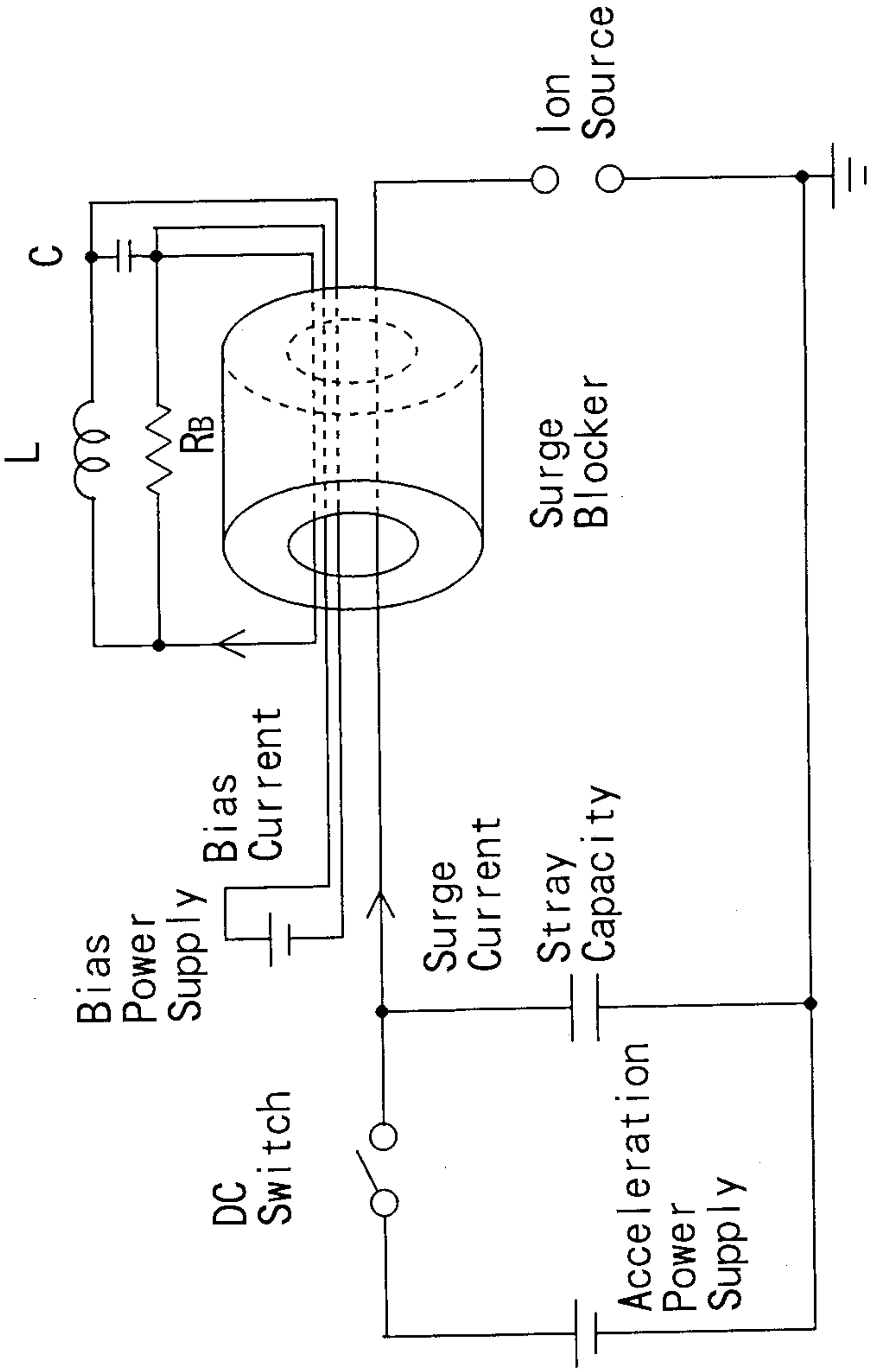

Fig. 1 The principle of the surge blocker.

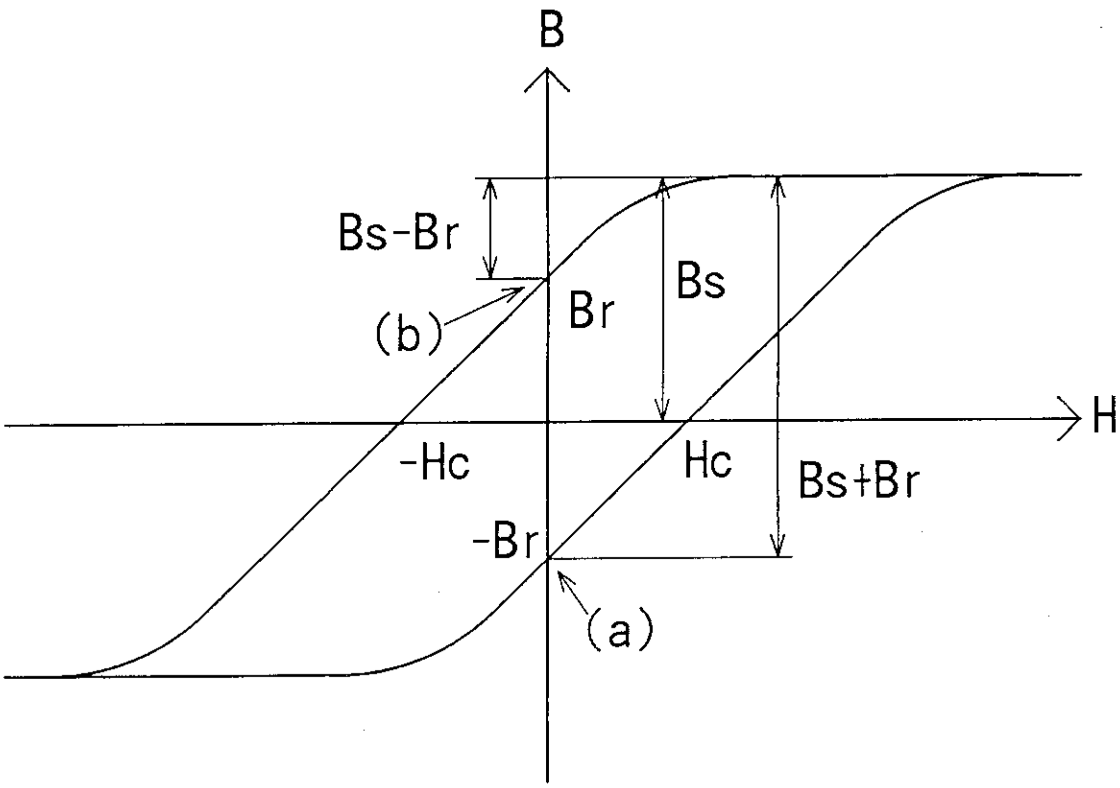

Fig. 2 Schematic diagram of the B-H curve of the magnetic material.

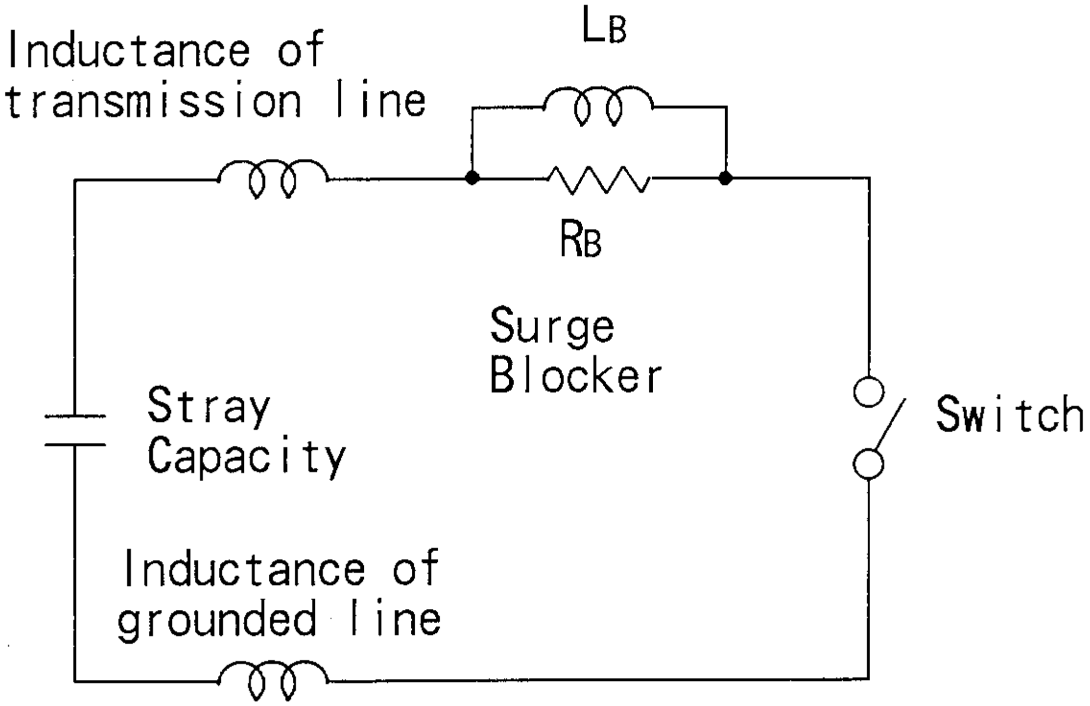

Fig. 3 The equivalent circuit of the surge blocker.

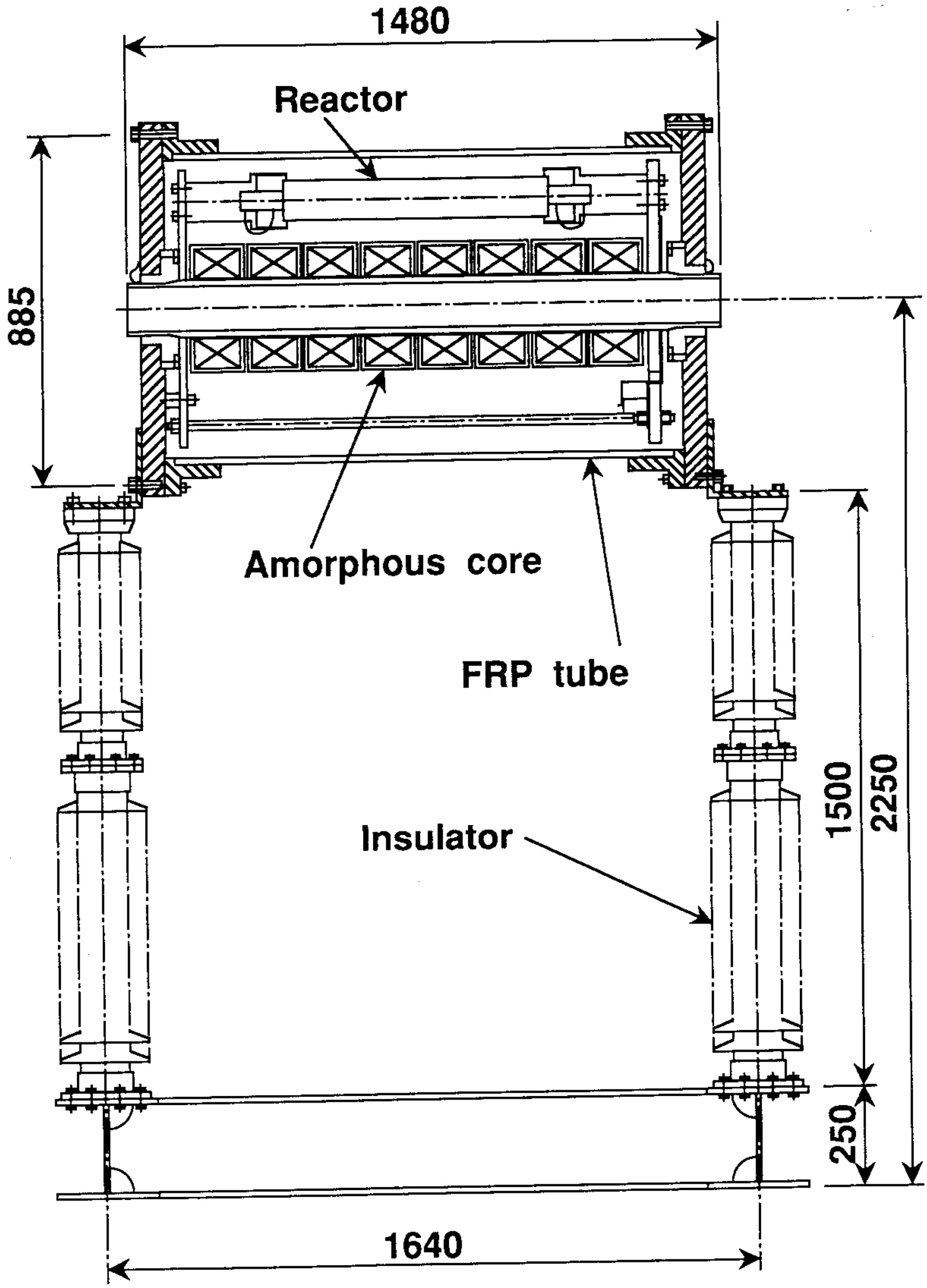

Fig. 4 The structure of the 350 kV amorphous surge blocker.

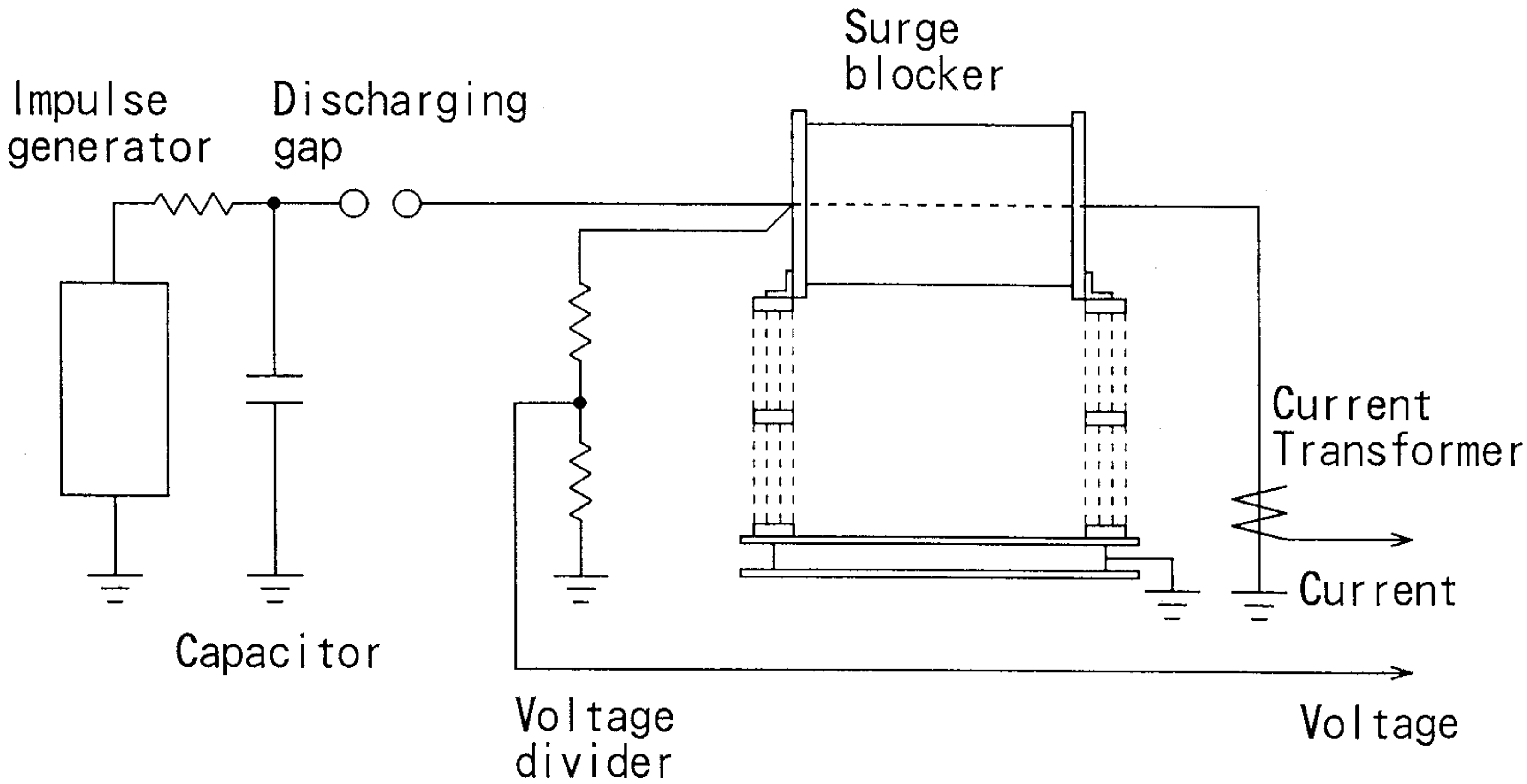

Fig. 5 The schematic diagram of the test circuit of the surge blocker.

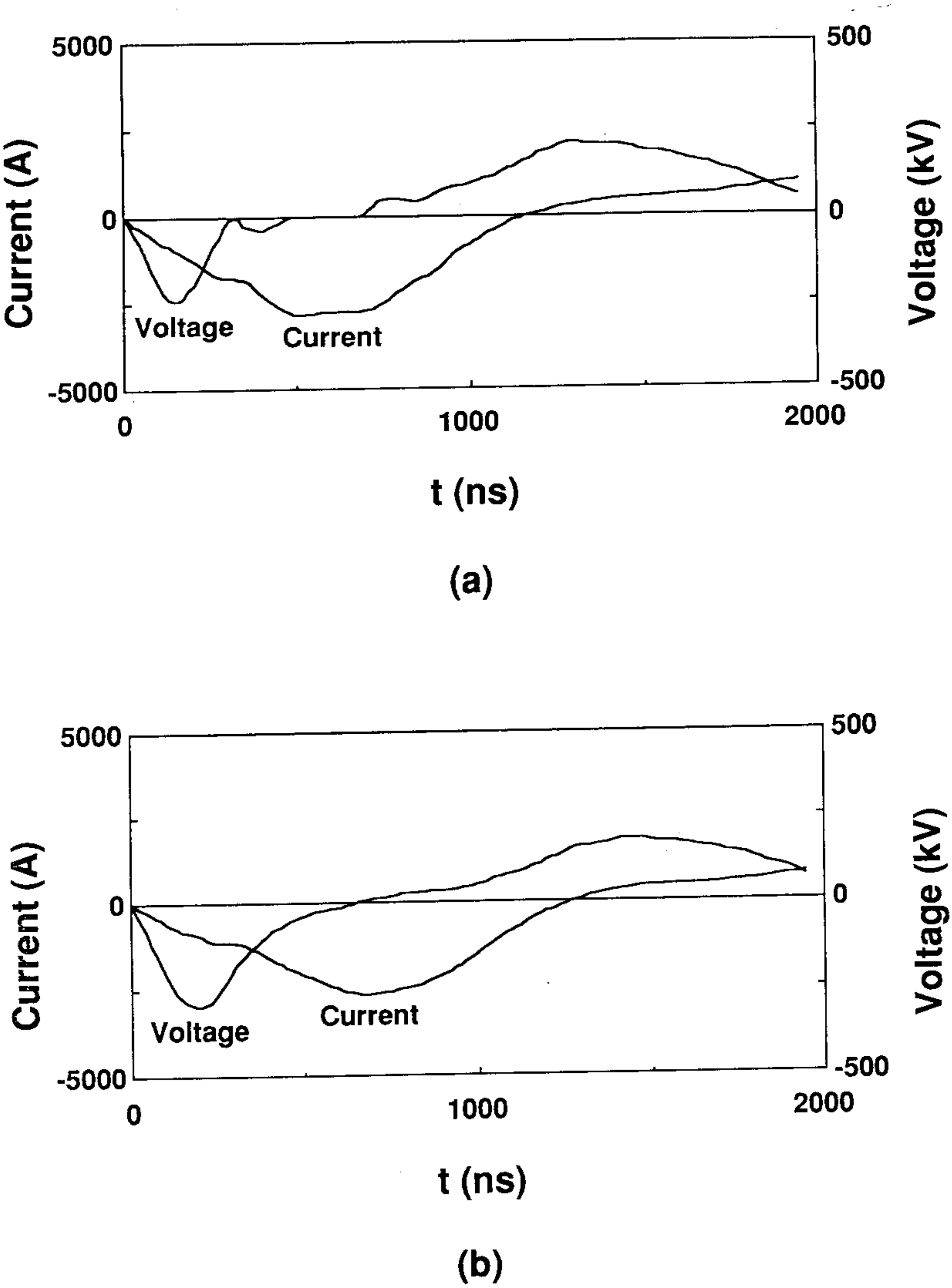

Fig. 6 Waveforms of the voltages applied to the surge blockers and the current.