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DEVELOPMENT OF A DC 1MV POWER SUPPLY TECHNOLOGY FOR NB INJECTORS

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Major issues of NBI power supplies are a high-speed switching, regulation and transmission of dc ultra high voltage, and suppression of surge energy input to the beam source at breakdown. A GTO(gate turn off thyristor) inverter type power supply where the control is performed at low voltage ac side was designed for the ITER NB. Based on the remarkable progress of a high power IEGT (injection enhanced gate transistor), the design of the inverter has been modified to increase an efficiency and compactness using such new elements. A power loss in the inverter is reduced to be 30% of the GTO inverter system. For the transmission line of the dc UHV with intermediate voltages, a disk shape multi-conductor bushing with a transmission line test chamber has been developed. Dimensions of the bushing are 1.8 m in diameter and 140 mm in thickness at the edge. Electric fields at the conductor surface and insulator surface were designed to be lower than 5 kV/mm and 7 kV/mm, respectively. An electric field at the bottom of the ground potential outer conductor was designed to be lower than 1.2 kV/mm to prevent particle levitation which triggers breakdowns. The prototype transmission line has passed the standard impulse test up to 1,300 kV. A dc UHV up to 1,175 kV was successfully sustained for 300 s. To prevent the electric damage of the beam source at the breakdown, core snubbers using Fe-based nanocrystalline soft magnetic materials are adopted to dissipate the surge energy.

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I. INTRODUCTION

Required functions of a power supply system for a MeV class negative ion based neutral beam injector(NBI) are to supply dc ultra-high voltage(UHV) with protection both of a beam source and the power supply itself from electric breakdowns. The breakdown of the NBI beam source is considered to be unavoidable phenomena for high power operation. When the breakdown occurs in the beam source, the power supply cuts off the short circuit. After certain period of interruption, the high voltage is turned on again to continue the beam injection. High voltage dc switches like a tetrode, GTO(Gate turn off thyristor) or IGBT(Insulated gate bipolar transistor) were utilized in the ion beam acceleration power supplies whose voltages were < 200 kV. Such dc switches can not be applied for the 1 MV power supply of negative ion based NBI, because reliability of the dc switch with a large number of elements becomes low. Therefore an inverter controlled power supply system has been developed[1-4]. The system eliminates the switch in the dc high voltage line.

A GTO inverter system based on the JT-60 N-NBI power supply[1-4] was designed for the ITER NB power supply[5,6]. According to the recent progress of the high power and high frequency semiconductors, the inverter using new element of IEGT(Injection enhanced gate transistor) has been designed to reduce power loss in the inverter.

Not only generation and control the dc UHV, but also transmission of the UHV from the power supply to the beam source was another R&D issue in the 1 MV NBI power supply system. A prototype transmission line with a multiple conductor bushing which is a key element has been developed in the ITER EDA[7] . Another important function of the NBI power supply is to operate the ion source without electric damage even the breakdown occurs. Though the main circuit current is cut off by the high speed switching system like the inverter mentioned above, a stored energy at the stray capacitance can flow into the ion source independently. Surge suppression system is essential to reduce such energy input to protect the beam source from degradation of the voltage holding. Core snubber is one of the effective elements to block and absorb the stored energy input to the accelerator at the breakdown. Materials of magnetic core should be selected based on dynamic properties of the cores. A nanocrystalline magnetic material[8,9] is one of the candidates for the compact core snubber.

In the present paper, these key technologies developed at JAERI for the NB power supplies are reported.

II. A 1 MV POWER SUPPLY USING IEGT INVERTER

Conventional dc switch at the high voltage line can not be adopted for the UHV dc power supply for NBIs. The inverter controlled power supply has been developed in the JT-60 N-NBI power supply whose capacity is -500 kV, 64 A, 10 s[1-4]. Both the voltage regulation and high speed switching are controlled by the GTO inverter at the low voltage primary side of the dc power supply. The ITER NB acceleration power supply system whose capacity is -1,000 kV, 59 A, 1,000 s had been designed in EDA[5,6] based on the JT-60N-NBI power supply.

High power and high frequency elements are required to control MW power supply like the JT-60N-NBI and the ITER NB. IGBT(Insulated gate bipolar transistor) can control higher frequency than that of GTO, but capacity is smaller than that of GTO. Only GTO could be adopted in the JT-60 N-NBI in those days. Considering recent progress of high power semiconductor elements, design of the GTO inverter can be changed to high power IEGT (Injection enhanced gate transistor) inverter[10]. Performance of the IEGT is reaching the GTO in handling power which is higher than that of IGBT. Operational frequency is one order higher than that of GTO and similar to IGBT. Figure 1 shows the comparison of these semiconductor performances.

GTO requires powerful snubber circuit and gate power supply, because GTO is an element controlled by gate current. However IEGT does not need such a large snubber circuit and gate power supply. The IEGT is a gate voltage controlled element similar to IGBT. By adopting the IEGT inverter, a total electric loss in the inverter is reduced to 30 % of the GTO inverter. This means that a 1.6 MW loss in the GTO inverter at the ITER NB power supply can be reduced to 0.5 MW for the inverter output frequency of 150 Hz. A space for the gate power supply and the subber circuit surrounding the GTO can be reduced. As a result, a volume of the inverter panel will be decreased to 60 % of the original GTO inverter panel.

For the 1 MV power supply, three sets of a single phase inverter whose capacity is 1.64 MVA are connected in parallel for one phase of a transformer[5,6]. A circuit diagram of the IEGT single phase inverter is illustrated in Fig. 2. Nine sets of the inverter(three paralleled x three phase) are utilized for one stage of acceleration power supply to generate dc -200 kV. Five stage dc generators produce the 1 MV UHV with total 45 inverters. A schematic diagram of the dc 1 MV power supply controlled by the IEGT inverter is shown in Fig. 3.

Results of circuit analysis using EMTDC is shown in Fig. 4. A dc high voltage is ramped up during 50 ms, and then the load is switched on after 100 ms from the high voltage start. It was confirmed that the IEGT inverter system can control output stably by the simulation. The IEGT inverter can cut off the output any time when the breakdown is detected as the same as the GTO inverter system in the interrupting time of < 200 μs.

III. ULTRA HIGH VOLTAGE TRANSMISSION

A gas insulated transmission line is necessary to connect the UHV power supply and the beam source. One of crucial elements was a high voltage bushing for multiple conductors in the transmission line. A mock-up of the 1 MV transmission line with the bushing has been designed and fabricated in the ITER EDA[7]. The transmission line between the high voltage deck and the beam source has a complex geometry with a central large conductor which contains many bus bars and cables for a negative ion generator. Intermediate voltage conductors for the multi-stage accelerator are installed surrounding the central conductor. Potential of the central conductor is -1 MV. Different potential conductors of 200 kV step for intermediate grids to the 5 stage accelerator are mounted.

Design criteria of electric field strengths at the bushing and conductors was decided based on the reports for high voltage insulation in the gas[11-14]. Table 1 shows the design criteria of the electric field for the multi-conductor bushing. Figure 5 shows the corresponding points of the electric field on the bushing. The breakdown electric field is about 11 kV/mm at triple junctions of the insulator bushing attaching the metal flange and conductors. The design target is smaller than 7 kV/mm for the triple junctions. An insert electrode is necessary to reduce electric field concentration at the ground potential conductor attaching the bushing. Breakdown electric field is about 17 kV/mm at the surface of the insert electrode to the bushing edge. Design criteria was set as lower than 10 kV/mm. Particle levitation should be considered to avoid breakdown due to metal particle jump up from the ground potential conductor. Particle levitation electric field is about 1.8 kV/mm for 5 mm metal particles which was assumed at this design[11-13]. Distribution of all conductors and configuration of the bushing were adjusted to lower the electric fields.

A material of the bushing is alumina powder mixed with epoxy resin. This material is widely used for bushings for gas insulated substations(GIS) which are mainly ac transmission system. Dimensions of a disk shape bushing are 1.8 m in diameter, and 140 mm in thickness at the edge. This size is 90% reduction of the ITER NB transmission line. A configuration of the bushing is illustrated in Fig. 6. The bushing was mounted in the transmission line test chamber which is shown in Fig.7 [7]. The bushing was attached between two tanks. A testing high voltage was supplied from a feed through. A conductor of the feed through was connected to the central conductor of the bushing. Then the conductor at the other side connected to a bleeder resistor which was mounted at the edge of the tank. The intermediate voltages divided by the bleeder resistor were supplied to the intermediate conductors. Pressurized SF_6 gas of 0.5 MPa was introduced to the tank.

A standard impulse of 1.2x50 μs, -1,300 kV has been applied for three times without breakdown. After the impulse test, dc high voltage test has been conducted. Leak currents at both side of the bushing were measured separately. A dc high voltage up to 1,175 kV has been successfully sustained without breakdown for 300 s. The voltage corresponds the testing voltage of ITER NB power supply with considering 90% scaled model. Leak currents as a function of the applied voltage is shown in Fig. 8. The bleeder resistor was installed at the position illustrated in Fig. 7. The leak current of this side was a little higher than the other side. A small corona discharge appeared at the temporal wirings which connect between the bleeder resistor and conductors.

No breakdown occurred in the transmission line test chamber. No discharge trace has been observed all inner surfaces of the test chamber and the multi-conductor bushing by observation after the high voltage test. It was confirmed that the designed criteria of the electric field strength for the insulator with conductor is suitable for the 1 MV bushing fabrication.

IV. SURGE SUPPRESSION

The beam source accelerator is damaged by energy input from the power supply system at breakdown. It is important to continue the beam acceleration without degradation of voltage holding even after the breakdown. The beam source should be protected from electric damage due to the breakdown for stable beam acceleration. The input energy which gives the damage to the beam source accelerator is proportional to the stray capacitance of the power supply and to square of operating voltage ($1/2\ CV^2$). Reduction of stray capacitance is fundamental to reduce the stored energy to protect the accelerators. However, the higher voltage required for the MeV NBI produces a large quantity of stored energy. So, it is essential to use additional surge energy reduction system like core snubbers and reactors with resistors.

The input energy to the accelerator was designed smaller than about 1 joule for the low energy NBIs, namely positive ion based NBIs, where the accelerator gap length were about 10-20 mm and the operating voltages were lower than 200 kV[15,16]. However, an accelerator of negative ion based NBI has longer gap range of 50 cm for the 1 MeV acceleration. There are some reports that show the longer gap allow higher input energy. It was reported that 50 Joule was allowable at the experiment using a simple vacuum gap[17]. For the JT-60 N-NBI power supply, it was reported that the measured surge current and estimated input energy to the ion source was 3.4 kA and 8 joule, respectively[3]. In the ITER NBI power supply designed by JAERI, design target for the surge suppression was set as <3 kA and <10 joule[5].

To reduce the surge energy input to the beam source, core snubbers and reactors with resistors(LR) are utilized[5]. The LRs are adopted to components where the stray capacitance is concentrated such as insulated transformers. The LR is connected on the secondary output of the transformer to suppress the surge current from the stray capacitance between the secondary winding and the primary winding. Such reactor is a zero-phase reactance which can act as inductance only for surge current. It does not affect the normal current for the power supply operation. Stored energy at all other parts should be blocked. The core snubbers dissipate the surge energy flown from the stray capacitances which exists various parts of the high voltage. Therefore the core snubber should be installed at the nearest position from the beam source to block the surge input from these stray capacitances.

Performance of the core snubber is equivalent to the inductance with paralleled resistor. To absorb the energy at breakdown, the core material which has enough inductance without saturation is required. Magnetic core materials should have high saturation magnetic flux density and high permeability for high frequency surge. Inductance of the magnetic core is given by a following equation:

$$L = \frac{(4\pi \times 10^{-7} \times \mu_r \times S)}{le} \quad (H)$$

where μ_r is relative permeability, S is effective area of the core, and le is magnetic path length. High μ_r is essential for the effective core snubber system. It is necessary to see not only saturation magnetic flux, but also dynamic magnetic properties to choice core material for high frequency surge. For example, a Fe-base amorphous core has a high saturation magnetic flux of 1.5 T for static magnetic properties, however the dynamic magnetic properties is very low at high frequency region. Comparison of the magnetic properties for these materials is shown in Fig. 9 and Fig.10. Core snubbers using Fe-based nanocrystalline soft magnetic materials (FINEMET)^{P} [18] developed Hitachi Metals ltd. is a candidate for the core snubber in the MV NBI power supply. Magnetic materials which have higher magnetic saturation flux and higher permeability at high frequency region of MHz can make smaller core snubber system.

V. SUMMARY

Major subjects for the 1 MV NBI power supply system has been discussed. Generation, control, and transmission of the dc UHV, and surge suppression are essential issues for the 1 MV NBI power supply system. Described technologies in this paper are fundamental for the 1 MeV negative ion based NBI system. In addition to these technologies, noise reduction and surge suppression for the detailed part of control and diagnostic circuits are quite important for system reliability. Fixation of potential in power supply control circuit is required to avoid malfunctions and electric damages from the breakdown surge. Such countermeasures against the surge propagation have to be considered sufficiently at the design. In addition to this, it is necessary to take enough time to test and regulate the power supply system with spark gaps, dummy loads and real load of the beam source to complete the reliable system.

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REFERENCES

[1] M. Mizuno, et al.,”Power supply system for JT-60U N-NBI” IAEA Technical Committee Meeting, Naka(1991)259.

[2] K. Watanabe, et al.,Radiat. Phys. Chem. Vol. 49, No.6, 631-639(1997).

[3] T. Ohga, K. Usui, K. Ohmori, K. Watanabe, K. Ohshima, T. Itoh, M. Kawai, and M. Kuriyama,”High voltage power supply of negative ion based NBI for JT-60U”, Proc. 17th IEEE/NPSS Symposium of Fusion Engineering, 1091-1094(1997).

[4] K. Omori, et al.,”Improvement of the ion source power supply for JT-60 negative-ion based NBI”, Proc. 20th SOFT, Marseille, Sep.7-11,395-398(1998)

[5] K.Watanabe,et.al.; “Design of ITER NBI power supply system”, JAERI-Tech, 97-034, July, 1997.

[6] K. Watanabe, et. al.,;”Design of neutral beam injection power supplies for ITER, , JAERI-Tech, 2003-033, March 2000.

[7] T. Tsunematsu, et al.,” ITER activities in Japan”, Fusion Sicence and Technology, vol.42,, 75-93(2002).

[8] S.Nakajima, et al., Nucl. Instrum. Methods in Phys. Res. A 331- 318(1993).

[9] K.Watanabe, et al., Rev. Sci. Instrum., vol. 69, No. 12, 4136-4141(1998).

[10] F. Saito, et al., “Development of magnetet power supply for J-PARC 50 –GeV synchrotron”,Proc. 1st Annual Meeting of Particle Accelerator Society of Japan and 29th Linear Accelerator Meeting in Japan, Aug.4-6, Funabashi, 114-116(2004)(in Japanese).

[11] C.M.Cooke, et al.; ”Influence of particles on AC and DC electrical performance of gas insulated systems at extra high voltage”, IEEE Trans. Power Appar. & Syst., PAS-96, No.3(1977).

[12] F.Endo, et.al.; “Control of particle motion and reliability improvement in high-voltage DC GIS”, Proc. The 11th International conference on gas discharge and their applications, I-346(1995).

[13] F.Endo, et.al.; ”Particle-initiated breakdown characteristics and reliability improvement in SF6 gas insulation”, IEEE Trans. Power Delivery, PWRD-1, No.1, 58(1986).

[14] Goshima, et.al., Komae Research Lab Report No. T97027, March 31, 1998 (in Japanese).

[15] M. Matsuoka, et al.,IEEE Trans. On Plasma Scie., vol.PS-12, No.3, 231-232(1984).

[16] K.Watanabe, et al., Journal of Plasma and Fusion Research, Vol.69, No.10, 1229(1993),(in Japanese).

[17] F.Bottigilioni and J.P.Bussac, Physica 104C, 248(1981).

[18] K.Watanabeet al., Rev. Sci. Instrum., vol. 69, No. 12, 4136-4141(1998).

Table 1 Electric field simulation of the bushing.

No.	Position	Insulation	E-designed (kV/mm)	Edsgn criter (kV/mm)	Ebd (kV/mm)
1	Triple junction	Surface	6.0	7.0	11
2	Triple junction	Surface	6.7	7.0	11
3	Insert electrode	Solid(epoxy)	9.2	10.0	17
4	Concave point	Surface	5.5	7.0	11
5	Triple junction	Surface	2.7	7.0	11
6	Concave point	Surface	5.0	7.0	11
7	Triple junction	Surface	1.8	7.0	11
8	Concave point	Surface	3.3	7.0	11
9	Triple junction	Surface	4.0	7.0	11
10	Insert electrode	Solid(epoxy)	2.2	10.0	17
11	Duct bottom	Gas	1.2	1.5	1.8
12	AG1 surface	Gas	5.0	5.0	8.8

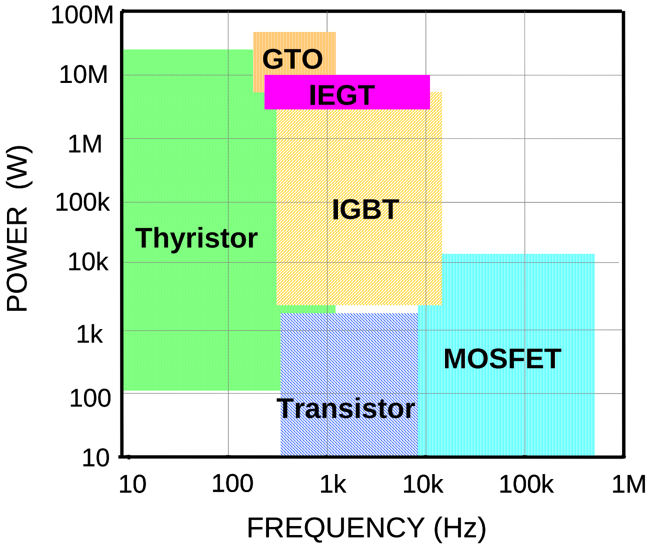


Fig. 1 Comparison of high power semiconductor elements.

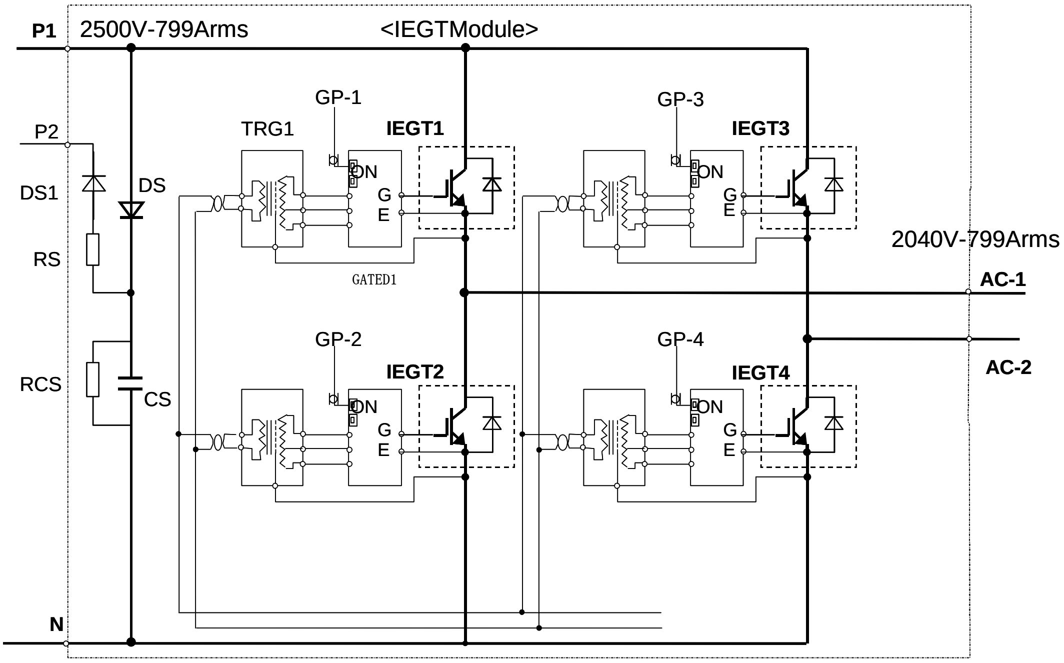


Fig.2 IEGT inverter system for the 1 MV NB power supply.

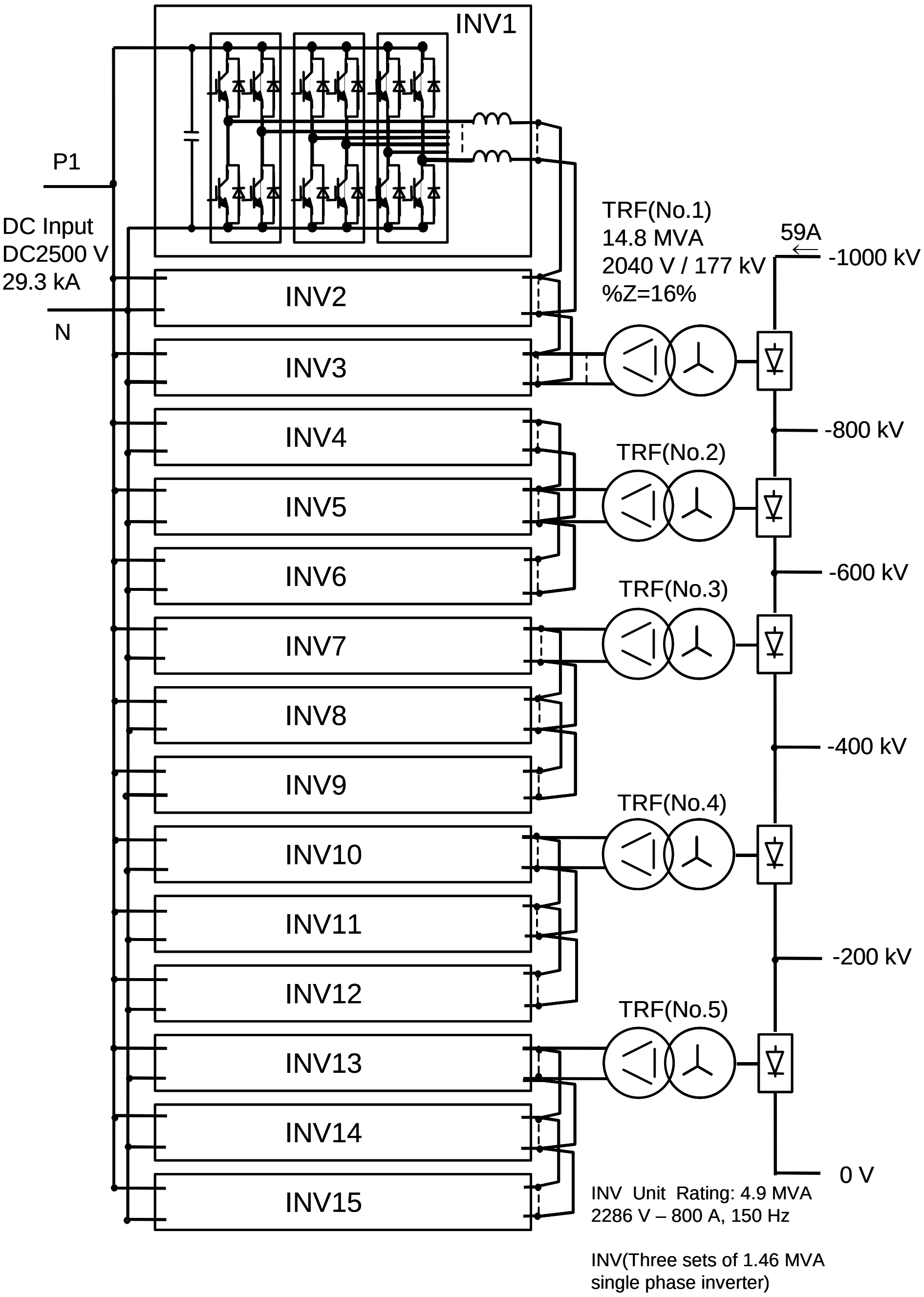
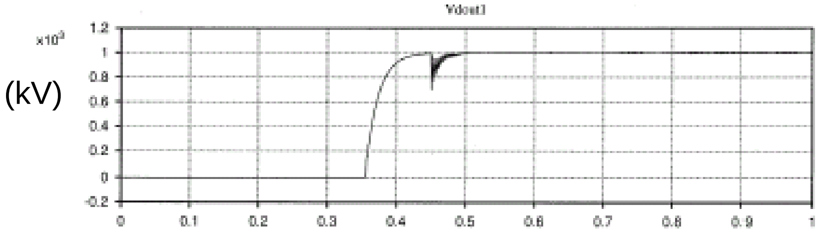
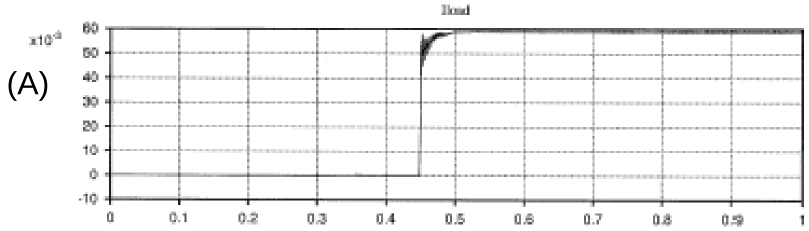


Fig.3 A dc 1 MV power supply for the negative ion accelerator controlled by IEGT inverter.



Output Voltage



Output Current

Fig. 4 Simulation of the 1 MV power supply with using EMTDC.

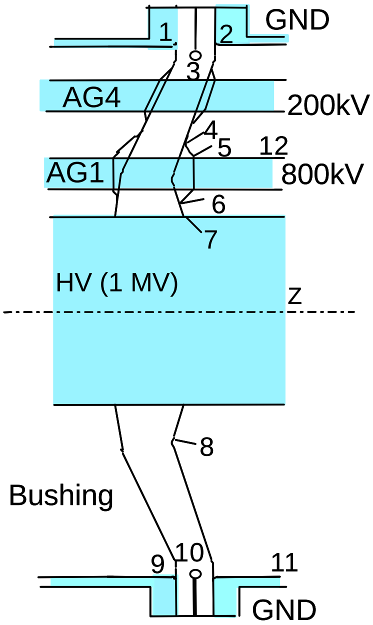


Fig.5 Important points for the bushing design.

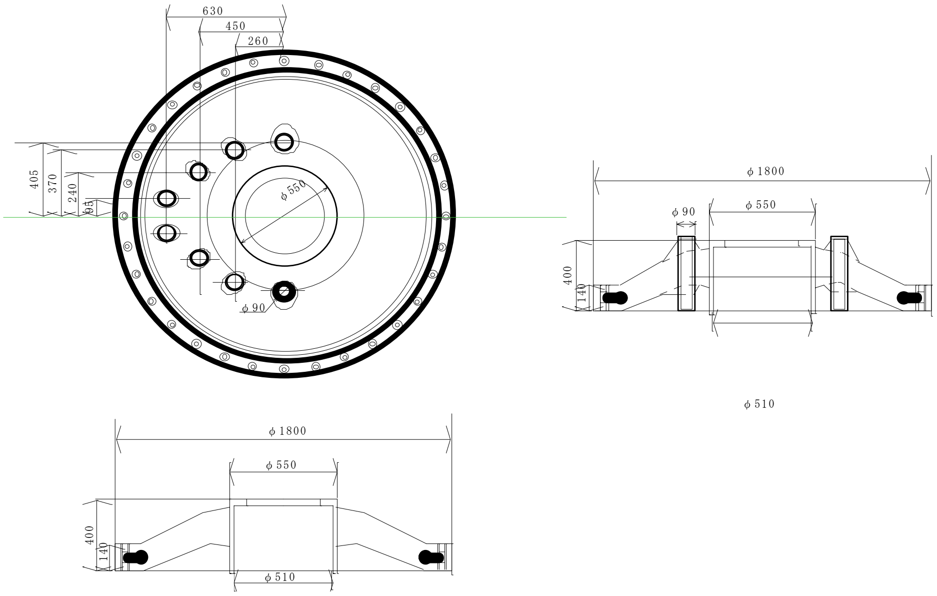


Fig. 6 A multi-conductor bushing for dc 1 MV transmission line with intermediate potential conductors.

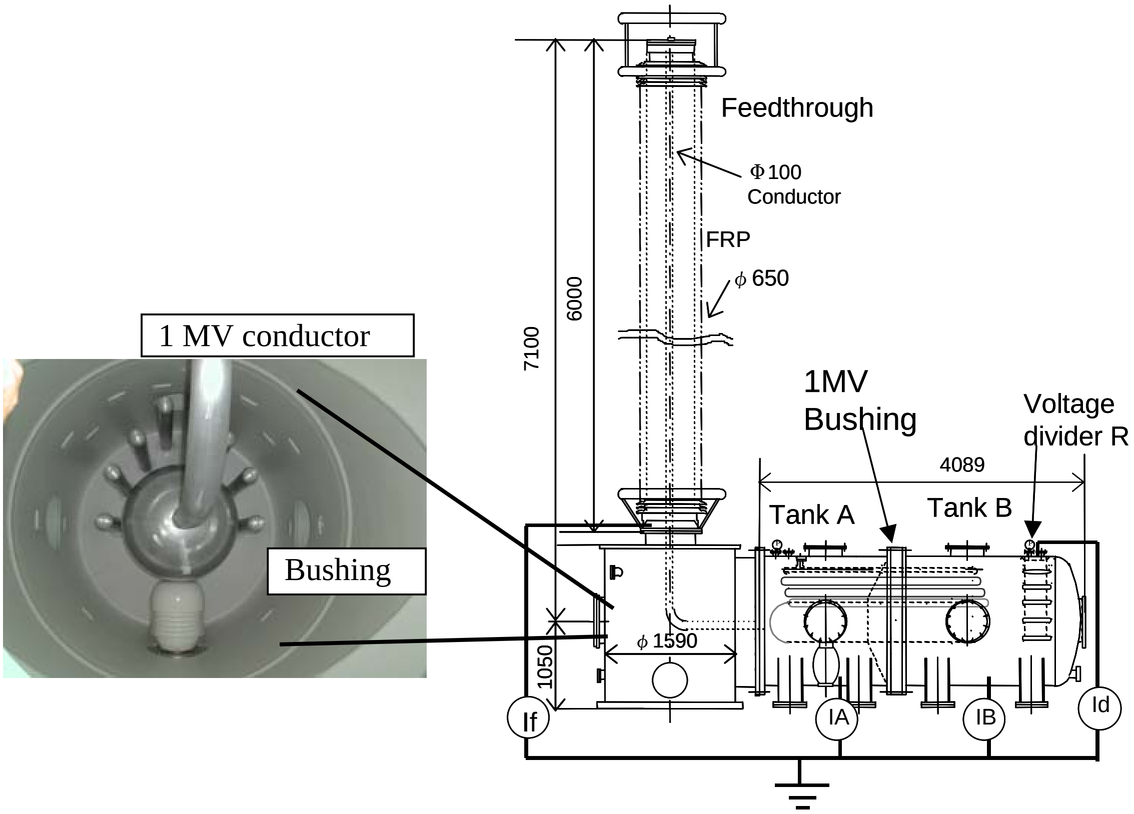


Fig.7 Prototype transmission line and a view of the bushing.

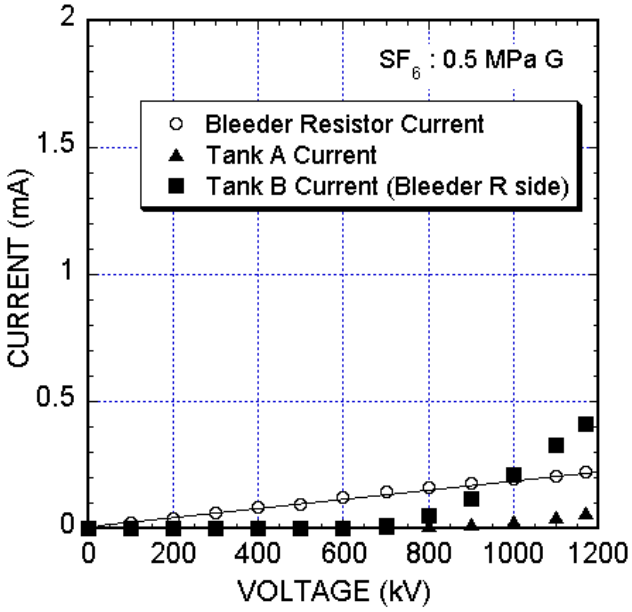


Fig.8 Leak current as a function of applied voltage.

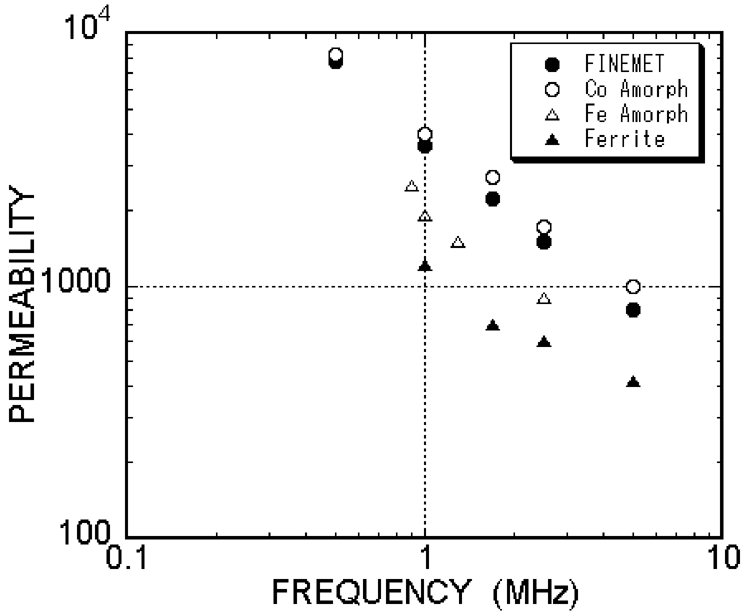


Fig.9 Permeability of magnetic materials as a function of frequency.

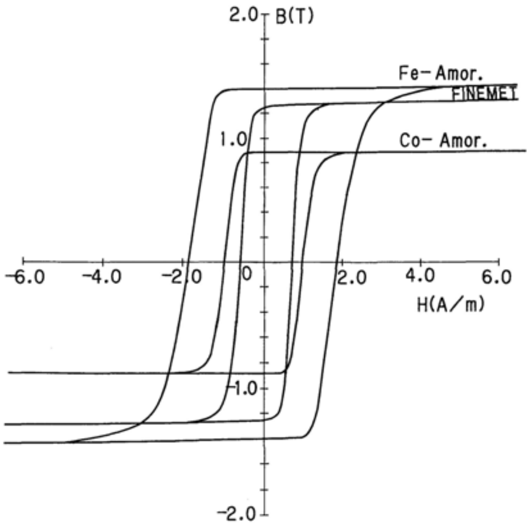


Fig. 10 B-H curve of magnetic materials for core snubber.