Development of a core snubber for the neutral beam injector on EAST

Cai-Chao Jiang, Chun-Dong Hu, Ya-Hong Xie, Sheng Liu, Shi-Yong Chen, Zhi-Min Liu, Yong-Jian Xu, Li-Zhen Liang, and Yuan-Lai Xie

Citation: Review of Scientific Instruments **87**, 123302 (2016); doi: 10.1063/1.4972883
View online: http://dx.doi.org/10.1063/1.4972883
View Table of Contents: http://aip.scitation.org/toc/rsi/87/12
Published by the American Institute of Physics

Articles you may be interested in

Retarding field analyzer for the EAST plasma boundary
Review of Scientific Instruments **87**, 123503123503 (2016); 10.1063/1.4971317

Use of solid N2 surfaces in metastable particle detection
Review of Scientific Instruments **87**, 123110123110 (2016); 10.1063/1.4972278

Development of plasma assisted thermal vapor deposition technique for high-quality thin film
Review of Scientific Instruments **87**, 123501123501 (2016); 10.1063/1.4969052

A physics package for rubidium atomic frequency standard with a short-term stability of 2.4 × 10-13 τ-1/2
Review of Scientific Instruments **87**, 123111123111 (2016); 10.1063/1.4972567

SHIMADZU
Excellence in Science
Powerful, Multi-functional UV-Vis-NIR and FTIR Spectrophotometers
Providing the utmost in sensitivity, accuracy and resolution for applications in materials characterization and science
• Photovoltaics • Ceramics • DNA film structures
• Polymers • Thin films • Packaging materials
• Coatings • Inks • Nanotechnology
• Paints
Click here for accurate, cost-effective laboratory solutions

Development of a core snubber for the neutral beam injector on EAST

Cai-Chao Jiang,[1,2] Chun-Dong Hu,[1,2] Ya-Hong Xie,[1,a)] Sheng Liu,[1] Shi-Yong Chen,[1] Zhi-Min Liu,[1] Yong-Jian Xu,[1] Li-Zhen Liang,[1] and Yuan-Lai Xie[1]
[1]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China*
[2]*Graduate School, University of Science and Technology of China, Hefei 230026, China*

(Received 5 July 2016; accepted 9 December 2016; published online 28 December 2016)

A 4-MW ion source was developed for the neutral beam injector (NBI) on Experimental Advanced Superconducting Tokamak (EAST). Breakdown nevertheless can happen during ion source conditioning and routine operations and is deleterious to the high-power ion source. To protect this ion source, a core snubber was designed to absorb the breakdown energy of the EAST-NBI ion source. A prototype core snubber was developed and tested using the ion-source test bed. The results show that with a core snubber, short-circuit currents at different high-power voltages were about one-tenth of the current without the snubber. The residual energy of the distributed capacitors had been absorbed successfully and the core snubber does protect the source from damage during breakdown. The results verified the successful development of a core snubber for the EAST-NBI. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4972883]

I. INTRODUCTION

The neutral beam injector (NBI) is an effective method for plasma heating and current driving on the Experimental Advanced Superconducting Tokamak (EAST).[1,2] Two beam lines were installed on the EAST with a beam energy of 80 keV and a beam power of 4 MW.[3,4] The ion source[5] is one of the more important parts of the EAST-NBI, which comprises the plasma generator and accelerator; the former generates plasma and the latter extracts the ions from the plasma and accelerates them to form an energetic ion beam. When the ion source is in operation, the accelerator can easily break down, especially during the conditioning mode of the ion source.[6] With huge amounts of energy distributed in the capacitors of the high-voltage power supply and transmission lines, the accelerator can potentially be damaged if no equipment is available to absorb the breakdown energy, usually above 5 J. To protect the ion source during breakdown, a core snubber was designed and assembled outside of the transmission line, which absorbs this energy and limits the maximum current through the ion source. For the power supply system with the core snubber (see Fig. 1), all transmission lines supplying power will be connected to the ion source through the core snubber. Also, the core snubber will be installed close to the ion source to absorb the energy during breakdown.

II. DESIGN OF CORE SNUBBER FOR NEUTRAL BEAM INJECTOR ON EAST

The physical design of the core snubber is based on the experimental and technical expertise and the Fink–Baker–Owren nonlinear transformer theory.[7] The maximum arc current deduced is

$$\hat{i}_A = 0.38 k_e C V_0 \gamma, \tag{1}$$

where C is the capacitance of the distributed capacitors, V_0 is the accelerator voltage, and k_e is a coefficient when there is a parallel inductance. The factor γ is deduced using the equivalent circuit of Fig. 1 and given by

$$\gamma = \frac{\left[1 + (r_0/r_1)^{1/2}\right]}{2N_C N_L N_T^{3/2} w} \left(\frac{\pi r_1 V_0}{2.5 B \rho C}\right)^{1/2}, \tag{2}$$

where r_0 and r_1 are the inner and outer radii of the ferromagnet, respectively, w is the width of one of the ferromagnets, N_L is the number of layers of the metal tape wound for the core, N_C is the number of ferromagnets, B is the sum of the saturation flux density B_s and residual flux density B_r, and ρ is the resistivity; these are the specifications for each ferromagnet. Equation (2) indicates three methods to achieve small values for γ:

(i) increase B or ρ by selecting strong ferromagnetic materials;
(ii) increase the number of ferromagnets N_C;
(iii) arrange a suitable ratio for the inner and outer radii of the ferromagnet r_0/r_1.

The ferromagnetic material made by DeltaMax has good specifications and is used in the EAST-NBI core snubber; for specifications of the core snubber see Table I.

The effect of ratio r_0/r_1 on γ is evident in Fig. 2. Clearly, γ decreases rapidly when the ratio r_0/r_1 increases from 1 to 2.5, before leveling off. Considering space limitations and utilization efficiency, r_0/r_1 was chosen to be 2.5 or less.

The core snubber for the EAST-NBI was designed with several ferromagnets fitted together to form a cylinder. Each ferromagnet was insulated by a thin insulator. The whole ferromagnet was surrounded by a coil circuit that supplied bias power. The transmission lines for the ion

a)Author to whom correspondence should be addressed. Electronic mail: xieyh@ipp.ac.cn

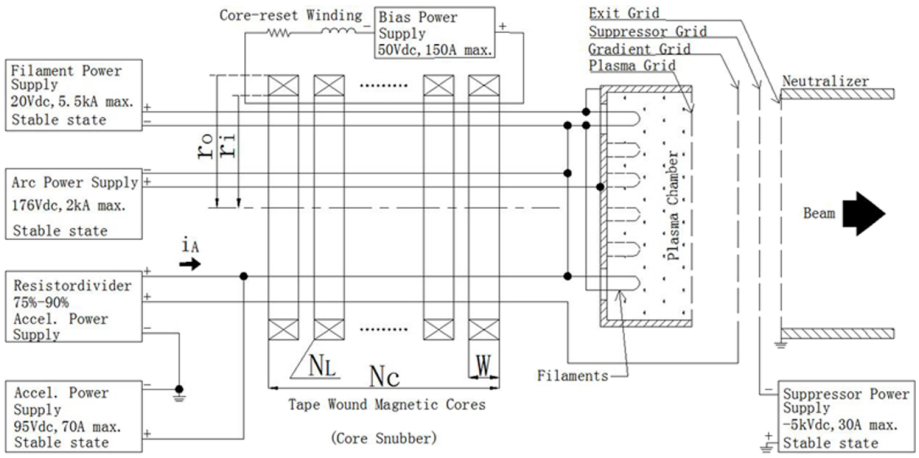

FIG. 1. Power supply system and core snubber for the EAST-NBI.

TABLE I. Specifications for the material in a core snubber.

Characteristic	Parameter
Saturation flux density, B_s	0.8 T
Residual flux density, B_r	0.55 T
Resistivity, ρ	0.45 $\mu\Omega$·m

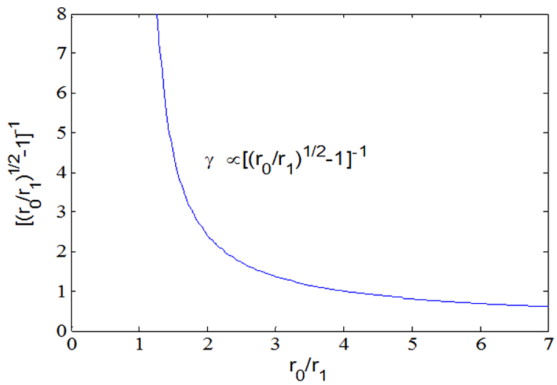

FIG. 2. Dependence of coefficient γ on the ratio of the inner and outer radii of a ferromagnet.

source go through the core snubber, and the energy can be absorbed as eddy currents in the core snubber during breakdown.

The structure of the core snubber for the EAST-NBI is shown in Fig. 3 and its parameters are listed in Table II. The snubber was designed as a hollow cylinder comprising 310 enameled wire loops (4 mm × 5.5 mm). The cylinder was insulated using epoxy with an inner diameter of 305 mm. There are 70 core ferromagnets installed each with an inner diameter of 154 mm and an outer diameter of 253 mm. Each ferromagnet was insulated from the others. The cylinder has a total length of 2230 mm with an inner diameter of 146 mm.

III. EXPERIMENTAL SETUP AND PERFORMANCE TESTING OF THE CORE SNUBBER

The core snubber was tested using the ion-source test bed. A schematic of the experimental setup of the EAST-NBI core snubber is shown in Fig. 4. P_{HV} denotes the accelerator high-voltage power supply, C the capacitor of the equivalent capacitance, L_P the current limiting reactor of the high-voltage

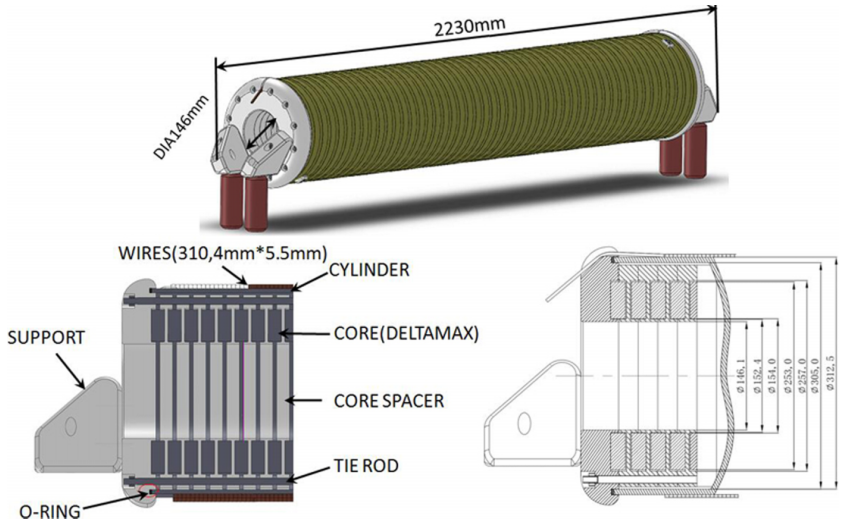

FIG. 3. Structure of the EAST-NBI core snubber.

TABLE II. Parameters of the core snubber.

Items	Parameter
Width, w	20 mm
Lamination, d	0.05 mm
Inner radius, r_1	154 mm
Outer radius, r_0	253 mm
Laminations, N_L	762 tape turns
Conductor turns, N_T	1
Cores, N_C	70

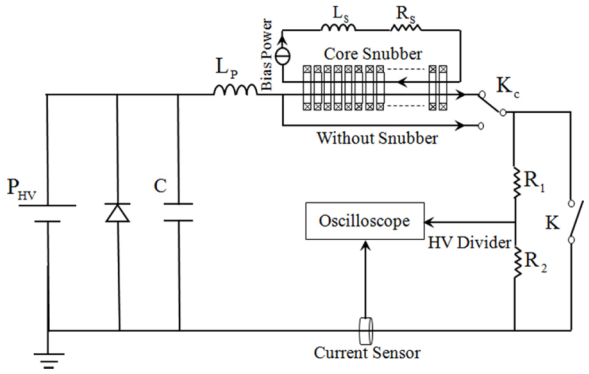

FIG. 4. Schematic of the experimental setup for the core snubber.

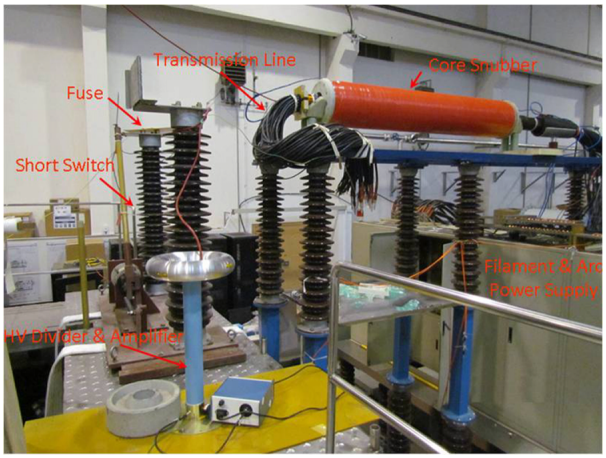

FIG. 5. Photo of the core snubber on the ion source test bed taken during testing.

power supply, K_C a switch to insert the core snubber, K a shorting switch to simulate breakdown of the ion source, and R_1 and R_2 are the divider resistors of the high-voltage bleeder. There is a fuse in the circuit with a diameter 0.128 mm, length 15 cm, and weight 0.015 g; its resistance is 0.345 Ohms at room temperature and fuses at an energy of 5.5 J. Measured using sensors, the voltage and current were displayed and stored with an oscilloscope. Figure 5 shows a photo of the core snubber on the ion source test bed taken during testing.

The test experiment was started with a high voltage of 30 kV, which was increased in steps of 10 kV. The results of the measured current are given in Fig. 6; those of the shorting test at 70 kV are given in Fig. 7.

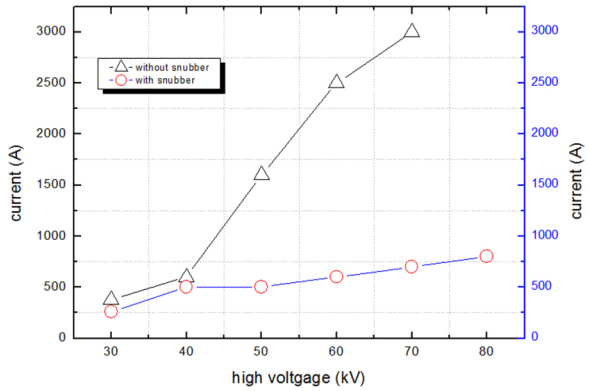

FIG. 6. Measured current with and without the snubber during short-circuiting of the high-voltage power supply.

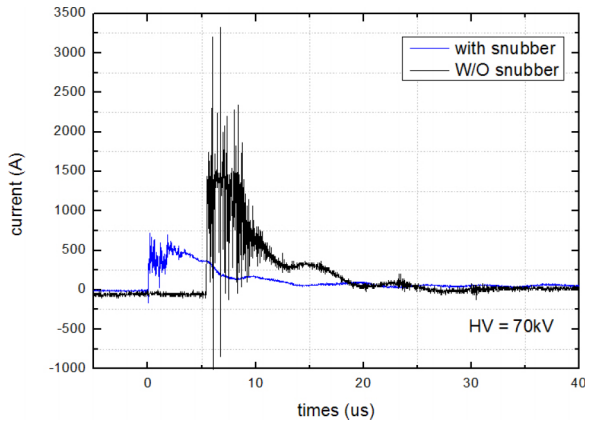

FIG. 7. Short-circuit current with and without the snubber at 70 kV.

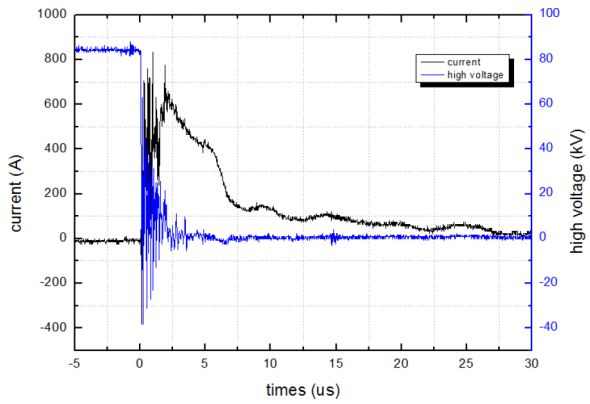

FIG. 8. Shorting current with the snubber at 80 kV.

In the low high-voltage (30–40 kV) region, the short circuit current is not reduced significantly in a comparison with and without the snubber (Fig. 6). Nonetheless, in the high-voltage region, the short-circuit current is much lower. In particular, a short current of 3000 A without the snubber decreases to about 700 A with the snubber. Moreover, with the snubber, the fuse was not damaged, implying the energy imposed on the ion source was less than 5.5 J. Therefore, the snubber has performed as designed, absorbing the energy at breakdown and protecting the ion source.

The designed high voltage of the EAST-NBI is 80 kV, but as short-circuiting the high voltage power supply without

the snubber is dangerous, only a test with the core snubber at 80 kV was conducted (Fig. 8). The maximum short-circuiting current was about 800 A, much lower than that for 70 kV without the snubber. A prototype was developed and tested using the ion source test bed at high voltages up to 80 kV.[8,9] This demonstrates that the core snubber can protect the ion source during breakdown, and its design and performance meet the requirements of the EAST-NBI system.

IV. CONCLUSION AND DISCUSSION

A core snubber was designed for the high-power ion source of the EAST-NBI system. The test results demonstrate that with a core snubber, the short-circuit current was much lower than tests without the core snubber. The residual energy of the distributed capacitors was able to be absorbed by the core snubber. If breakdown occurs, the ion source will be protected from damage. To date, four snubbers have been developed and installed in the EAST-NBI system, and they have performed well in the three campaigns of EAST experiments.

In performance tests for the core snubber of the EAST-NBI, only the short circular current was measured. The energy absorbed by the core snubber was not calculated and this aspect is to be analyzed and tested.

ACKNOWLEDGMENTS

The authors are sincerely grateful to the other members of EAST NBI team for their continuous encouragement and support. This work was supported by National Natural Science Foundation of China (Contract No. 11505225 & 11405207), the International Science and Technology Cooperation Program of China (Contract No. 2014DFG61950), and Foundation of ASIPP (Contract No. DSJJ-15-GC03).

[1]S. Wu, Fusion Eng. Des. **82**, 463 (2007).
[2]Y. X. Wan, J. G. Li, and P. D. Weng, Plasma Sci. Technol. **8**, 253 (2006).
[3]C. D. Hu and N. Team, Plasma Sci. Technol. **17**, 1 (2015).
[4]C. D. Hu, Y. J. Xu, Y. L. Xie, S. Liu, Z. M. Liu, P. Sheng, Y. H. Xie, L. Z. Liang, and N. Team, Chin. Phys. Lett. **32**, 052901 (2015).
[5]Y. H. Xie, C. D. Hu, S. Liu, Y. J. Xu, L. Z. Liang, Y. L. Xie, P. Sheng, C. C. Jiang, and Z. M. Liu, Rev. Sci. Instrum. **85**, 02B315 (2014).
[6]Y. H. Xie, C. D. Hu, S. Liu, L. Z. Liang, Y. J. Xu, Y. L. Xie, C. C. Jiang, P. Sheng, J. Li, and Z. M. Liu, Nucl. Instrum. Methods Phys. Res., Sect. A **727**, 29 (2013).
[7]J. H. Fink, W. R. Baker, and H. M. Owren, IEEE Trans. Plasma Sci. **8**, 33 (1980).
[8]C. D. Hu, Y. H. Xie, Y. L. Xie, S. Liu, Y. J. Xu, L. Z. Liang, C. C. Jiang, J. Li, and Z. M. Liu, Rev. Sci. Instrum. **87**, 02B301 (2016).
[9]L. Z. Liang, Y. Wang, X. X. Zhao, C. D. Hu, S. Liu, Y. H. Xie, C. C. Jiang, Y. J. Xu, Y. L. Xie, and P. Sheng, Phys. Scr. **90**, 045603 (2015).