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Investigation of the adhesive bonding technology for the insulator structure of EAST neutral beam injector

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A key issue on the development of EAST ion source was the junction design of insulator structure, which consists of three insulators and four supporting flanges of electrode grid. Because the ion source is installed on the vertical plane, the insulator structure has to withstand large bending and shear stress due to the gravity of whole ion source. Through a mechanical analysis, it was calculated that the maximum bending normal stress was 0.34 MPa and shear stress was 0.23 MPa on the insulator structure. Due to the advantages of simplicity and high strength, the adhesive bonding technology was applied to the junction of insulator structure. A tensile testing campaign of different junction designs between insulator and supporting flange was performed, and a junction design of stainless steel and fiber enhanced epoxy resin with epoxy adhesive was determined. The insulator structure based on the determined design can satisfy both the requirements of high-voltage holding and mechanical strength.
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I. INTRODUCTION

The neutral beam injection has been a promising method for plasma heating and current drive (H&CD) in magnetic confinement fusion devices.[1–6] The Experimental Advanced Superconducting Tokamak (EAST) is going to be equipped with two neutral beam injectors (Fig. 1), and each has a capability of 50–80 keV, 2–4 MW, 10–100 s deuterium beam injection.[7–9] The EAST neutral beam injector is equipped with the common long pulse source (CLPS) based on positive ions, which is composed of a magnetic cusp bucket plasma generator and a tetrode accelerator with multiple slits as shown in Fig. 2.[10–12] The accelerator is composed of three insulators and four acceleration grids, consisting of plasma grid (PG), gradient grid (GG), suppressor grid (SG), and exit grid (EG). Each grid is divided into 4 segments and each segment has 14 molybdenum rails. The grids are mounted on the corresponding supporting flanges, which connect to the high power supply. The cooling water runs through the inner of rails, so it has good performance of heat removing.

A key issue on the development of EAST ion source was the junction between insulators and supporting flanges. The three insulators and four supporting flanges should be jointed as an insulator structure, which needs to meet the requirements of high-voltage holding, mechanical strength, and vacuum seal. Specifically, the ion source is installed on the vertical plane, thus the insulator structure has to withstand large bending and shear stress due to the gravity of ion source. During the beam acceleration, a tiny crack between the insulator and supporting flange will cause serious electrical breakdowns, and even worse, there is an enormous risk that the ion source may rupture and drop off. So reliable mechanical property of the insulator structure is highly required.

Therefore, a mechanical analysis was carried out for the insulator structure, to estimate force acting on it. For EAST-NBI ion source, an adhesive bonding technology was applied to the junction between insulator and supporting flanges. A comprehensive test campaign has been planned and implemented in order to find the best adhesive bonding technology, including insulator material, surface treatment, and connecting structure. A voltage holding testing was implemented for the insulator structure using the proposed adhesive bonding technology. Finally, an enhanced mechanical structure through the epoxy resin stick was discussed.

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II. MECHANICAL ANALYSIS OF INSULATOR STRUCTURE

The force analysis of EAST ion source is also shown in Fig. 1. Through the supporting flange of EG, the ion source is fixed on the vacuum vessel with bolts. Hence, the whole ion source can be treated as statically determinate cantilever beams. Obviously, the largest bending and shear stress acts on the surface between supporting flange of EG and insulator. The mechanics equilibrium equation of this surface is

$$\begin{cases} F - mg = 0 \\ M - mgL = 0 \end{cases}, \tag{1}$$

where m is the mass of the ion source and L is the distance between the center of mass and this surface. And all the surfaces are assumed as ideal surface.

The upper surface has the largest deviation from the horizontal center axis, thus the maximum bending normal stress is

$$\sigma_{\max} = \frac{M}{W}, \tag{2}$$

where W is bending resistance coefficient. For the surface between supporting flange of EG and insulator (as shown in Fig. 2), the bending resistance coefficient is

$$W = \frac{(a+2\delta)\cdot(b+2\delta)^2}{6} - \frac{ab^2}{6}. \tag{3}$$

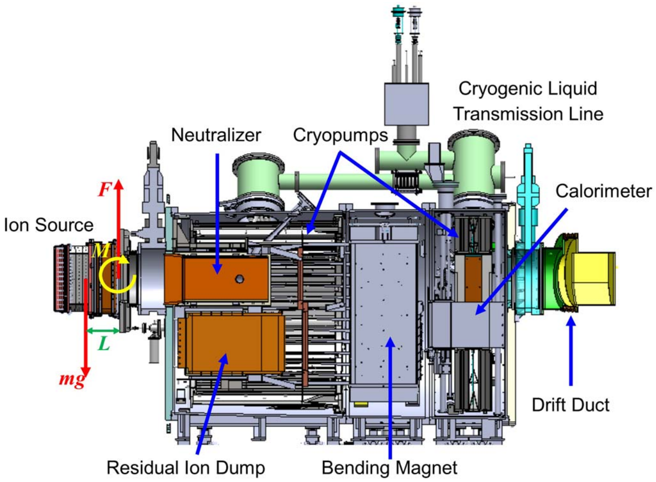

FIG. 1. CAD drawing of the EAST neutral beam injector. Since the ion source is installed on the vertical plane, the insulator structure has to withstand large bending and shear stress due to the gravity of ion source.

On the horizontal axis, the maximum shear stress is

$$\tau_{\max} = \frac{F S_{z\max}^*}{2 I_z \delta}, \tag{4}$$

where $S_{z\max}^*$ is the static moment of the surface below the horizontal axis and I_z is the inertia moment of the surface. For the surface between supporting flange of EG and insulator, these two moments are

$$\begin{cases} S_{z\max}^* = \dfrac{a+2\delta}{2} \cdot \dfrac{(b+2\delta)^2}{4} - \dfrac{a}{2} \cdot \dfrac{b^2}{4} \\ I_z = \dfrac{(a+2\delta)(b+2\delta)^3}{12} - \dfrac{ab^3}{12} \end{cases}. \tag{5}$$

Finally, considering the known conditions of $m = 550$ kg, $a = 325$ mm, $b = 711$ mm, $\delta = 20$ mm into the above equations, the maximum bending normal stress and shear stress on the surface between supporting flange of EG and insulator can be calculated as $\sigma_{\max} = 0.34$ MPa and $\tau_{\max} = 0.23$ MPa, respectively.

TABLE I. The mechanical properties of epoxy adhesive.

Parameter	Quantity	Test norms
Shear stress	28.9 MPa (25 °C)	ASTM D1002
	27.6 MPa (−55 °C)	
Tensile stress	31 MPa (25 °C)	ASTM D638
Compressive stress	51.7 MPa (25 °C)	ASTM D695

III. JUNCTION DESIGN OF INSULATOR STRUCTURE

Based on the mechanical analysis of the insulator structure, the adhesive bonding technology is simple and suitable for the junction between insulator and supporting flanges. However, more detailed analysis and test are required to determine the final design. Considered the mechanical and insulating performance, the epoxy resin and polyimide are available for insulator of EAST ion source. Especially, the epoxy resin was glued with the glass fiber to further enhance the mechanical strength. The material of supporting flange is 304 stainless steel, which has good corrosion resistance and formability. Note that the 304 stainless steel is the alloy of the carbon steel and the trace elements Cr, Mo, Ni, Mn, and Ti. Under the atmosphere condition, a continuous and dense passive film is easy to produce on the surface of 304 stainless steel. This passive film may lower the activity of adhesive bonding surface, thus reducing the adhesive strength.

Among the applicable adhesive for both materials of insulator and supporting flange, the epoxy adhesive Hysol EA9309.3NA was chosen, which had the same insulating and sealing properties of the epoxy resin. The mechanical properties of this epoxy adhesive are indicated in Table I. Since the gap length between each two grids demand a high accuracy,[13] adhesive thickness should be carefully controlled. There are micro glass beads of 0.13 mm in the adhesive, thus the minimum adhesive thickness is 0.13 mm.

Besides the bonding material and adhesive, the proper manners of surface treatment and adhesive coating as well as pressure setting, adhesive thickness, and curing condition are all key factors. Particularly, pre-bake in the oven will be

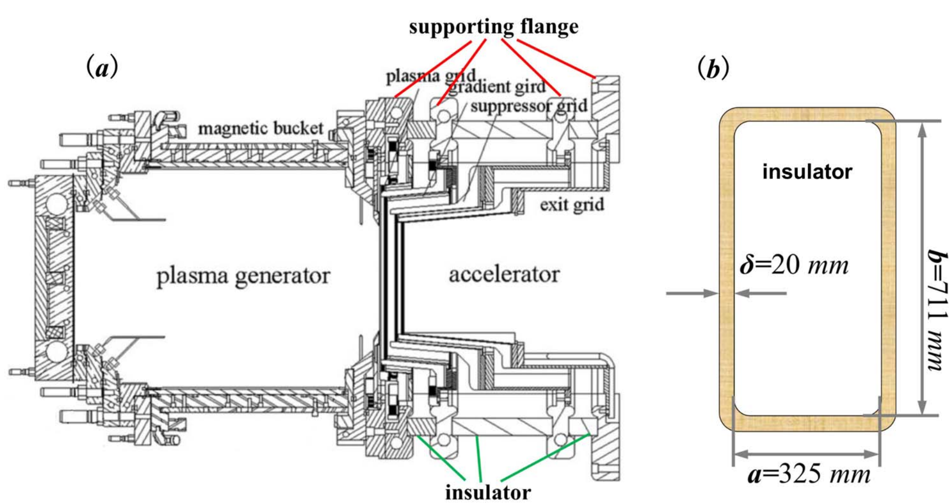

FIG. 2. The sketch of EAST ion source and sectional dimensions of insulator. The insulator structure is composed of three insulators and four supporting flanges.

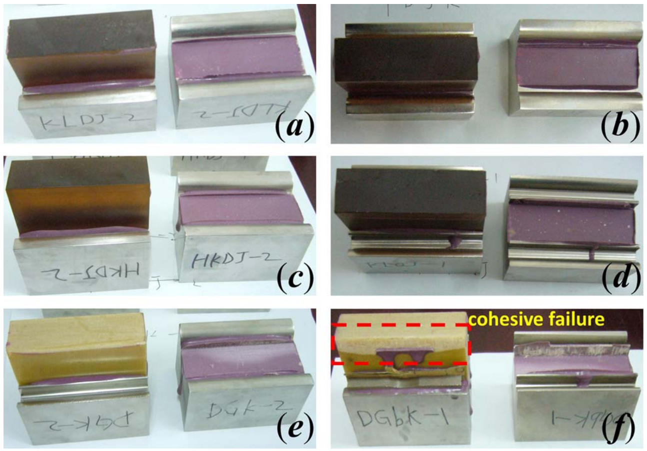

FIG. 3. Specimens of junction design (*a*)–(*f*) and comparison of broken sections after tensile testing. The adhesive appears purple color.

TABLE II. Tensile testing results.

Junction design	Destructive load (N)	Tensile strength (MPa)
(*a*): polyimide	12072	10.1
	18621	15.5
(*b*): polyimide, abrasive blasting	19484	16.2
	13078	10.9
(*c*): polyimide, pre-bake	8456	7.0
	9549	8.0
(*d*): polyimide, embedded groove	22298	18.6
	33961	28.3
(*e*): fiber enhanced epoxy resin[a]	**27775**	**23.1**
	32731	**27.3**
(*f*): fiber enhanced epoxy resin, edge stripe	34456	28.7
	32168	26.8

[a]Design (*e*) is chosen for the insulator structure of EAST ion source.

checked in the test, which has contributed to the solidification of adhesive in some way. Embedded design or abrasive blasting on the supporting flange is also the considered method to enhance the adhesive properties.

IV. TENSILE TESTING CAMPAIGN

As shown in Fig. 3, the junction design of specimens for tensile testing is connector between stainless steel and polyimide (*a*)–(*d*) or fiber enhanced epoxy resin (*e*) and (*f*). Each specimen is the junction between one insulator and two similar stainless steels, to simulate the actual insulator structure. And the two stainless steels are fixed on the tensile testing machine with two bolts. The area of adhesive bonding surface is 12 cm^2 and each surface has been treated to reach the environmental requirement for working in vacuum. A normal design in the field of electrostatic accelerator is applied to the supporting flange of the designs (*a*), (*b*), (*c*), and (*e*), as shown in Fig. 4. The ring shape at the edge of the supporting flange is used to reduce the concentration of electric field and increase the voltage holding capability.[14] Furthermore, the design (*b*) adopts abrasive blasting technology on the adhesive bonding surface of stainless steel, and the specimens of design (*c*) are baked in the 80 °C oven for 4 h after adhesive coating. In order to embed the insulator in the stainless steel, a groove in design (*d*) and two edge strips in design (*f*) are added on the surface of stainless steel. These two designs are expected to enlarge the adhesive bonding surface to enhance the adhesive strength.

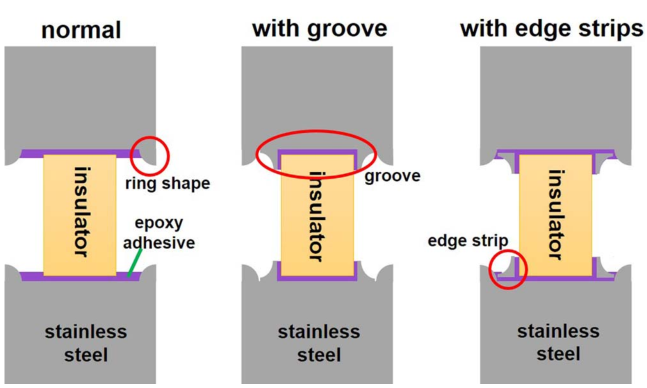

FIG. 4. Mechanical shapes of different supporting flange designs: normal, with groove and with edge strips. The groove is directly machined and formed on the stainless steel, but the edge stripes are bonded on the surface with the epoxy adhesive.

The tensile tests were performed in the temperature of 22 °C, the humidity of 50%, and curing time of 24 h. The tensile testing machine is equipped with a climate chamber and a data acquisition system for recording the strain load and temperature signals. The speed of strain load is 500N/min. Two specimens were tested for each design.

The tensile testing results are listed in Table II, and can be summarized as follows: (1) the selected adhesive has stronger bonding strength with the fiber enhanced epoxy resin than polyimide; (2) abrasive blasting on the adhesive bonding surface has not remarkable advantage; (3) pre-bake process is counterproductive when compared with curing in the room temperature; (4) the embedded designs of groove and edge stripe do enhance the bonding strength. According to the above results analysis, the design (*e*), junction of stainless steel and fiber enhanced epoxy resin with epoxy adhesive, is applied for the accelerator of EAST ion source. Although enhancing the bonding strength, the embedded design may lead to a voltage holding problem by changing the electric field. And the tensile strengths of the specimens of design (*e*) are far greater than the requirement of insulator structure.

The tensile strength is also different between the two specimens of each junction design. It is indicated that the adhesive coating process is very important to the bonding results. The adhesive process involves the quantity and uniformity of the adhesive on the bonding surface, which is operated by the engineer, thus resulting in a certain distinction in the adhesive strength for the actual insulator structure. From the broken sections in Fig. 3, it can be observed that for all the specimens, the vast majority of the adhesive (in purple color) remains on the surface of stainless steel, but little on the surface of the insulator. That is, most of the joint failures of these specimens are interface damage, and mainly located on the bonding surface of insulator. But the cohesive failure of epoxy resin is accompanied on the specimen of design (*f*),

TABLE III. Voltage holding test results.

Voltage (kV)	Leakage current (μA)	Holding time (s)
10	0	>300
20	3	>300
30	0	>300
40	2	>300
50	2	>300
60	3	>300
70	6	283
80	20	227
90	66	154
100	137	72

where a long piece of epoxy resin is broken and sticks to the adhesive on the surface of stainless steel.

V. VOLTAGE HOLDING TEST AND ENHANCED MECHANICAL STRUCTURE

Based on the proposed junction design, the insulator structure of EAST ion source was assembled completely. Then, a voltage holding test for the insulator structure was carried out at room temperature and standard atmosphere. The static high voltage was applied on the second insulator (i.e., between the supporting flanges of GG and SG), which is needed to hold a voltage of ~70 kV during the operation. The test results are listed in Table III. The maximum leakage current is only 137 μA. When the high voltage is below 60 kV, the insulator structure can operate above 300 s. And even the high voltage is 80 keV, the holding time is longer than 100 s, which still satisfies the operation demand.

Besides, an enhanced mechanical structure through the epoxy resin sticks was used in the actual insulator structure as shown in Fig. 5. Four sticks connect the supporting flange of EG to the plasma generator. It is expected that a proper preload on the sticks can increase the mechanical strength of insulator structure.

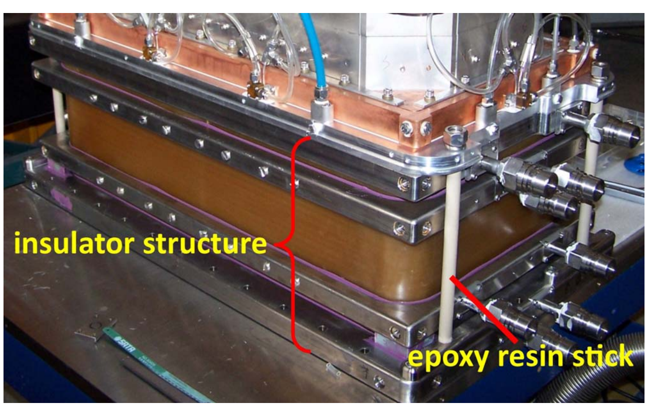

FIG. 5. Accelerator of EAST ion source. Actually, the insulator structure is the accelerator without the electrode grids. Four epoxy resin sticks were used to enhance the mechanical strength of the insulator structure.

VI. CONCLUSION

Due to the its own weight, the EAST ion source has to bear a large bending and shear stress on the insulator structure, that is composed of insulator and supporting flange of electrode grid. Hence, a mechanical analysis was performed on the accelerator of EAST ion source. The maximum bending normal stress $\sigma_{max} = 0.34$ MPa and shear stress $\tau_{max} = 0.23$ MPa act on the surface between supporting flange of EG and insulator. The adhesive bonding technology was applied to the connection between insulator and supporting flange. And a tensile campaign was carried out aimed at determining the optimal junction design, including the bonding material, adhesive, surface treatment, curing condition, and so on. A junction design of stainless steel and fiber enhanced epoxy resin with epoxy adhesive was selected, tensile strengths of which are far greater than the requirement of insulator structure. A voltage holding test also indicated that the insulator structure based on the proposed junction design can satisfy the requirement.

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