Overview of Development Status for EAST-NBI System*

HU Chundong (胡纯栋), XIE Yahong (谢亚红), XIE Yuanlai (谢远来),
LIU Sheng (刘胜), XU Yongjian (许永建), LIANG Lizhen (梁立振),
JIANG Caichao (蒋才超), SHENG Peng (盛鹏), GU Yuming (顾玉明),
LI Jun (李军), LIU Zhimin (刘智民)

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

Abstract The neutral beam injection (NBI) system was developed on the Experimental Advanced Superconducting Tokamak (EAST) for plasma heating and current driving. This paper presents the brief history, design, development, and the main experimental results of the R&D of neutral beam injector on the test bed and on EAST. In particular, it will describe: (1) how the two beamlines with a total beam power of 8 MW were developed; (2) the design of the EAST-NBI system including the high power ion source, main vacuum chamber, inner components, beam diagnostic system and sub-system; (3) the experimental results of beamline-1 on the summer campaign of EAST in 2014 and, (4) the status of beamline-2 and the future plan of EAST-NBIs.

Keywords: neutral beam injection, EAST tokamak, ion source, beamline

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(Some figures may appear in colour only in the online journal)

1 Introduction

The Experimental Advanced Superconducting Tokamak (EAST) is the first full superconducting tokamak in the world [1−3]. It was designed to operate with a 1 MA plasma current, 1000 s pulse length, and high elongation and triangularity. The scientific mission of the EAST project is to study the physical and engineering issues involved in steady-state operation, and to give technological support for fully superconducting future fusion reactors, such as ITER or DEMO. In order to achieve the scientific missions of the EAST tokamak, high power plasma auxiliary heating tools are needed, except for the ohmic heating.

The neutral beam injection (NBI) is one of the plasma heating tools that is used in fusion science [4]. It has a high plasma heating efficiency and clear physical mechanisms. Consequently, it has often been used as a plasma heating tool in fusion research devices all over the world [5−8]. ITER is an international fusion research device, which has 33 MW high neutral beam power for plasma heating [9]. JET has two beamlines with a total beam power of 34 MW, which is the highest power system on a fusion research device [10]. The KSTAR is another superconducting tokamak, which will develop a long pulse neutral beam injector of 300 s with beam power of 8 MW [11]. The ASDEX-U also has a neutral beam system with beam power of 18 MW. The JT-60U has several beam lines with a total beam power of 40 MW [12] and the DIII-D has four beam lines with beam power of 20 MW [13]. In China, the HL-2A has a beam line with beam power of 3 MW. A 5 MW beam power NBI system is currently under design for the HL-2M [14]. On the EAST, two beam lines with beam power of 8 MW need to be delivered into the core plasma [15].

2 Overview of EAST-NBI system

There are two NBI injectors with total beam power of 8 MW installed on the EAST tokamak to support the physical research [16]. The NBI-1 was proposed in 2008 and was approved by the central government in the middle of 2010 (financial support was given by the national development and reform commission). The NBI-2 was proposed in 2012 and approved and supported by the ministry of science and technology of the People's Republic of China in the beginning of 2013. The two beam lines are designed with tangential injection, which can be seen in Fig. 1. The injection directions of two beam lines are different to form the balance injection.

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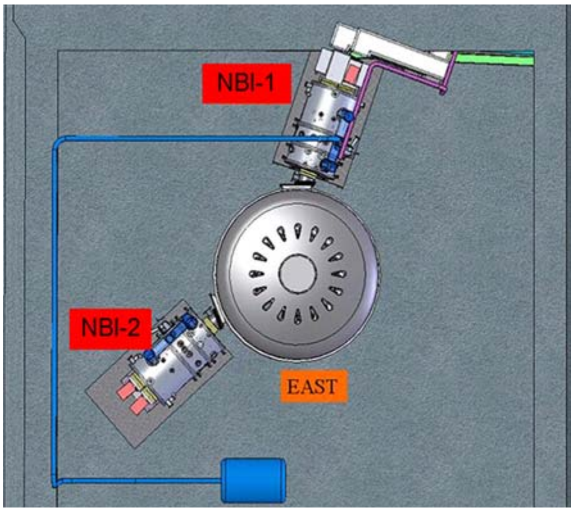

Fig.1 The bird view of EAST-NBIs

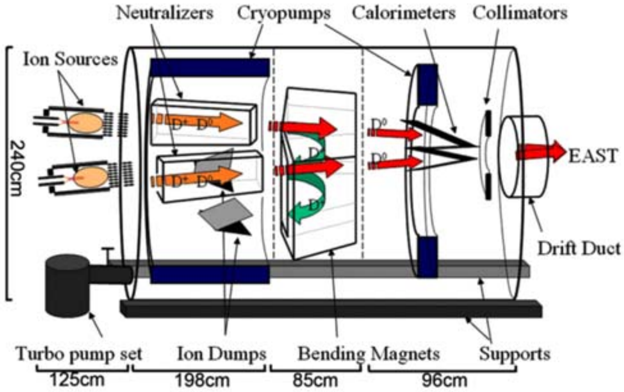

Fig.2 Schematic view of EAST-NBI

The two beam lines have the same structure [17]. The NBI-1 was installed on the EAST in the summer of 2013 and the first neutral beam was injected into the EAST plasma in August 2014. The NBI-2 now is under assembly and it will be finished in April 2015. According the schedule of EAST experiment, the NBI-2 will inject a neutral beam into the EAST plasma in May 2015.

2.1 The design of the EAST-NBI system

The EAST-NBI system includs two beamlines. Each beamline has the same structure and was shown in Fig. 2 [18]. The main design parameters can be seen in Table 1. The beamline consists of two ion sources, one vacuum chamber, two neutralizers, two bending magnets, two ion dumps, and two calorimeters. The NBI system also has many sub-systems, incluing a vacuum pump system, a control and data acquisition system, a diagnostic system, a gas puff system, a power system, and a cooling water system. One beamline has two ion sources. Each ion source has an independent beam channel and can be operated independently.

Table 1. The specifications of the EAST-NBI system

No.	Items	Specifications
1	NBI length	5800 mm
2	NBI width	2400 mm
3	NBI height	2400 mm
4	Weight	50 ton
5	Ion source number in one beam line	2
6	Beam cross section	12 cm × 48 cm
7	Beam species	Deuterium
8	Beam energy	50-80 keV
9	Beam length	10-100 s
10	Neutral beam power	2-4 MW (vary with beam energy)

2.1.1 The high power ion source

The hot cathode bucket ion source was employed on the EAST-NBI [19]. A schematic map of the ion source is shown in Fig. 3. The ion source contains a rectangle structure arc chamber and a four stage accelerator with slit type. There are 32 filaments installed on the top of ion source. Each filament is 160 mm long with diameter of 1.5 mm. The permanent magnets made of SmCo with intensity of 3500 Gs are installed surround the arc chamber and the electron dump to confine the plasma. The total loss area is about 1216 cm^2 (considering the multipole magnets) and the plasma volume is about 35.5 cm^3.

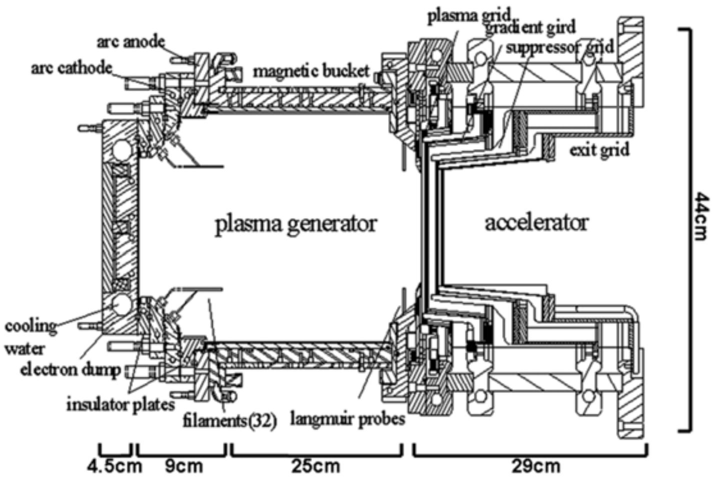

Fig.3 The schematic map of hot cathode bucket ion source

The tetrode accelerator with slot apertures was used on the EAST-NBI ion source [20,21]. It contains a plasma grid (PG), a gradient grid (GG), a suppression grid (SG), and an exit grid (EG), which form the extraction-acceleration-deceleration electrostatic structure. The GG is used to adjust the extraction electric field by changing the voltage applied on GG. The SG is used to suppress the electrons getting into the arc chamber. The accelerator with slot apertures has high transparency (60%). The cooling water of the accelerator goes through the inner pipe of grid, so it has good heat-removal efficiency. The designed beam extraction area is 12 cm×48 cm, and it can be adjusted by changing of the plasma gird mask plate. The plasma grid was designed with circular cross section, and was changed to a diamond cross section in 2014. The main size of the accelerator can be seen in Fig. 4. The beam divergence angle in Y direction as a function of beam perseverance of hydrogen gas was tested with a circular shaped and diamond shaped PG, and the results are shown in Fig. 5.

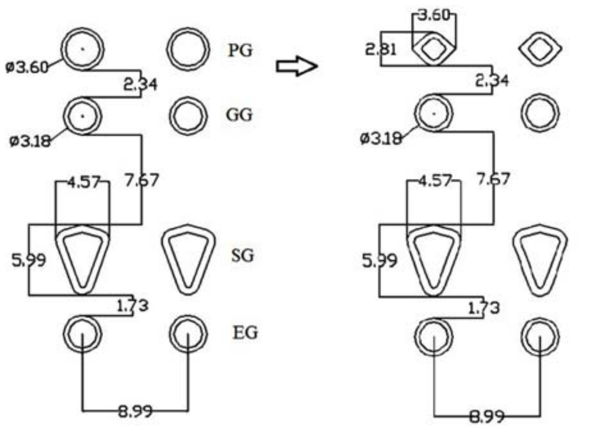

Fig.4 Schematic map of accelerator for the high current ion source

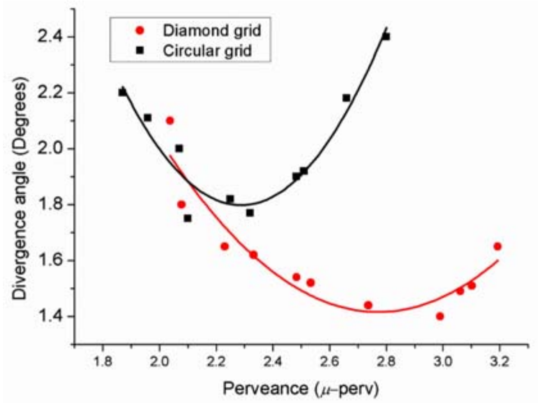

Fig.5 Divergence angle of Y direction as a function of beam perseverance of beam energy of 50 keV

2.1.2 The main vacuum chamber and inner components

The main vacuum chamber has three parts in a cylindrical shape with a diameter of 230 cm, which can be seen in Fig. 2. The first part is 180 cm long, the second part is 76 cm long, and the third part is 79 cm long. Two ion sources are connected with the first part with two ion source isolation valves. Other beamline inner components are installed in the main vacuum chamber, which can be seen in Fig. 6 [18]. The rear cryopump, neutralizers, and ion dumps are installed in the first part. The bending magnets are installed in the second part, and the calorimeters and the front cryopump are installed on the third part. Besides, there are many ports, which are used for the cooling water inlet and outlet, the diagnostic and power supply signals connection, and spectral diagnostics. The main vacuum chamber is connected with the EAST tokamak via the drift duct.

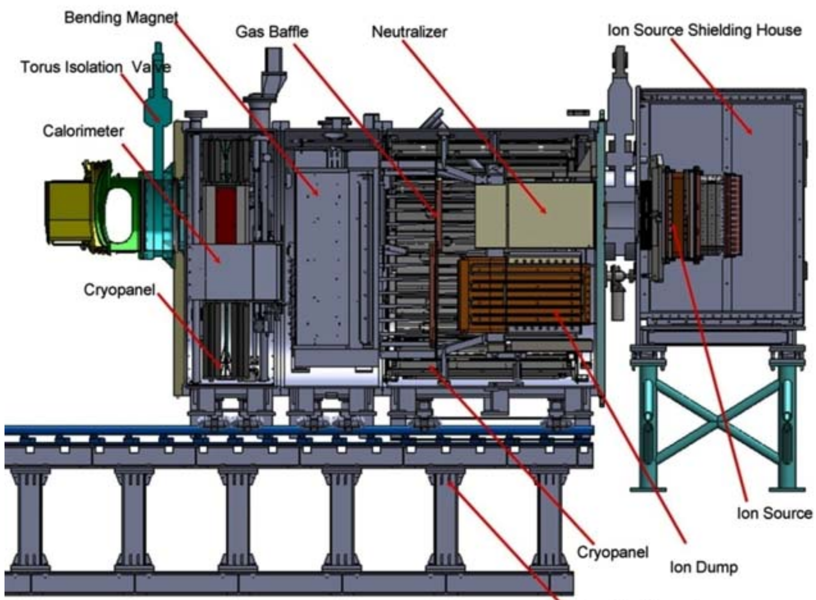

Fig.6 A schematic draw of inner components of beam line

The neutralizer is used to transfer the positive ions into energetic atoms by capturing an electron. The EAST-NBI neutralizer is a rectangular structure with 480 mm width, 140 mm height, and 930 mm length. The gas target thickness in the neutralizer is from 3×10^{15} cm^{-2} to 9×10^{15} cm^{-2}. In order to get an optimum neutralizing efficiency, extra gas needs to be puffed into the neutralizer. The nominal gas pressure at the entrance of neutralizer is 0.05 Pa, and at the end of the neutralizer it is 0.03 Pa.

When the neutral beam can only pass through the powerful magnetic area in the EAST tokamak, the unneutralized ions need to be removed. The bending magnet with 180 degrees bending angle was designed to bend the ions in the mixed beam from the neutralizer. According to the ion beam parameters, an "H" shaped dipole magnet was designed with magnetic field of 1900 Gs. The magnetic field uniformity is higher than 85%. The maximum bending radius is 42 cm with the beam energy of 80 keV. The size of the magnet pole section is 140 cm×50 cm with a gap of 20 cm, considering the beam divergence. In order to remove the heat load on the magnetic coils, an active cooling water supply is designed. Meanwhile, the magnetic pole shield was mounted to protect the coil from the energetic beam.

When the beam passes through the bending magnet, the neutral beam goes straight and the ion beam is reflected by 180 degrees to the ion dump. In order to measure the beam parameters, such as beam power and beam profile, a moveable calorimeter was mounted in the downstream of beading magnet. When the neutral beam needs to be injected into the EAST plasma, the calorimeter should move down from the beam channel. The calorimeter and the ion dump have high power deposition, so they are designed with "V" shape to reduce the power density per unit area.

The ion dump consists of two pieces of panel with 119 cm length, 66 cm width and 50 cm height. The beam entrance area is 61 cm×36 cm. The total area is about 3.2 m^2. The ion dump is actively water cooled and the maximum temperature in the surface is less than 420 K [22]. On the back-plate of the ion dump, 40 thermocouples are installed to monitor the temperature rise.

The calorimeter has a similar structure to the ion dump. The two pieces of the panel are 77 cm length, 49 cm width, and 5 cm thickness. The beam entrance area is 49 cm×28 cm. The total area is about 2.5 m^2. There are 40 thermocouples installed in the back-plate of calorimeter to deduce the beam profile, beam divergence angle, and beam power.

Two cryopanels are mounted in the main vacuum chamber to supply high speed vacuum pump. Two cryopanels were developed for the structure of the EAST-NBI vacuum chamber, which can be seen in Fig. 7. The rear cryopanel is circular in shape with an area of 8 m^2. The front cryopanel is a plate shape with an area of 6 m^2. The flow direction of liquid nitrogen and helium is shown in Fig. 8. The total pumping speed is about 1.4×10^6 L/s when the helium temperature is 3.8 K. The vacuum pressure can reach to 1×10^{-6} Pa.

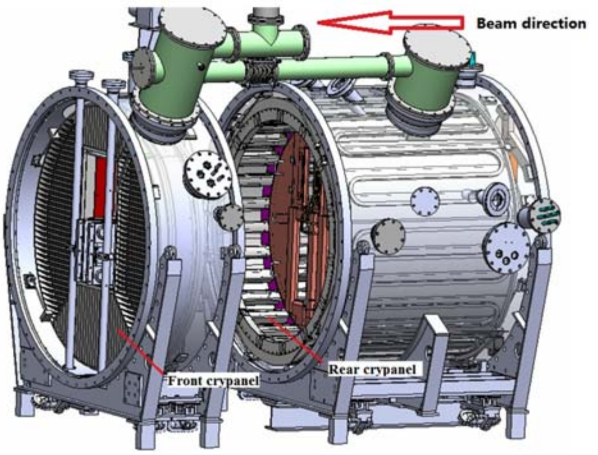

Fig.7 A schematic drawing of the cryopanels for EAST-NBI

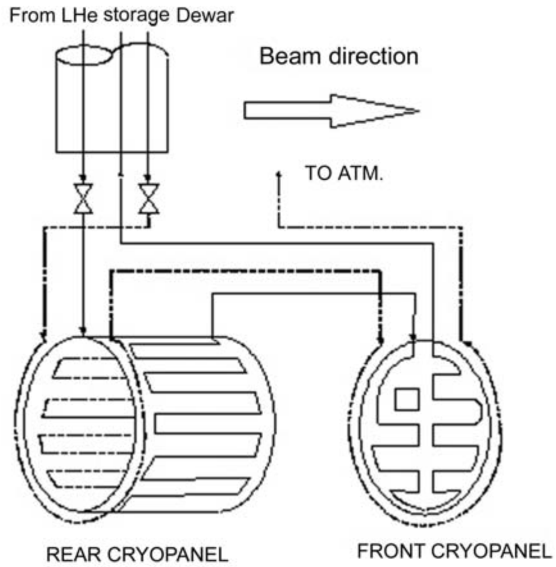

Fig.8 Sketch map of flow direction of liquid N_2 and He

2.2 Sub-system of EAST-NBI system

Several sub-systems are employed for the operation of EAST-NBI system, including the control and data acquisition system, the power supply system, the water cooling system, and the diagnostic system.

2.2.1 Control and data acquisition system

In order to support the EAST-NBI experiment, a distributed control system is employed [23]. The architecture of the control system can be seen in Fig. 9. It has three control layers: the remote monitoring layer, the server control layer, and the video monitoring network and the field control layer. Through the control system, the two ion sources can be operated individually.

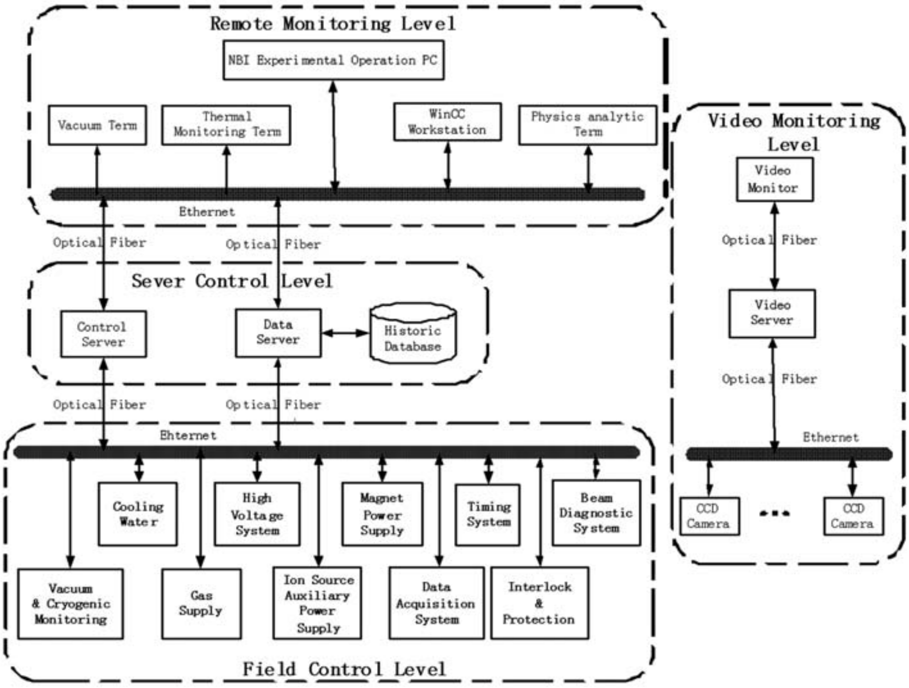

Fig.9 Architecture of the NBI control system

Data acquisition is used to supervise many of the parameters as well as the status of the EAST-NBI system [24]. Considering the elements distributed at several places, a distributed data acquisition system was employed that contains the field instrument and measurement devices, the servers, and the remote data processing terminals. All of the data can be collected and displayed in the control room.

2.2.2 Water cooling system

The water cooling system used to remove the heat load on each power deposition parts, including ion source, neutralizer, ion dump, calorimeter, drift duct and the beam collimators. The accelerator of EAST-NBI uses molybdenum material. So, the cooling water for the ion source is deionized water with a low oxygen content, whose electrical resistivity is larger than 4 MΩ·cm and whose oxygen content is less than 10 ppb. For the beamline, the deionzed water with 4 MΩ·cm will be enough. The water flow rates for the ion source and beamline are 14 L/s and 35 L/s, respectively.

2.2.3 Power supply system

The power supply system consists of low voltage power supply and high power supply, and the specification can be seen in Table 2 [25].

Table 2. Specifications of the EAST-NBI power supply system

Items	Voltage	Current
Filament power supply	20 V	5.5 kA
Arc power supply	200 V	3 kA
Snubber power supply	30 V	150 A
Accelerator power supply	100 kV	100 A
Suppressor power supply	−4 kV	20 A
Bending magnet power supply	80 V	600 A

The filament and arc power supply works at the high voltage potential of the accelerator power supply, which has a solid state architecture. In order to start the beam easily, the notch technology was employed on the arc power supply. This can also be regulated during the operation of the ion source for stable and long pulse operation [26,27].

2.2.4 Diagnostic tools [28−31]

In order to measure the plasma parameter and the beam quality, several diagnostic tools are employed on the EAST-NBI system, which are listed in Table 3.

Table 3. The diagnostic tools and their functions on EAST-NBI

No.	Items	Functions
1	Langmuir probe	Plasma density, electron temperature, plasma uniformity
2	Spectrum diagnosis	Beam species, beam divergence angle, beam energy
3	Water flow calorimeter	Beam power deposition
4	Thermocouple measurement	Beam profiles, beam power
5	RGA system	Working gas purity, background gas components

3 The performance of EAST-NBI

The ion source is a precision part and it needs to be conditioned. An ion source test bed was developed and used to condition the new ion source and to optimize the performance of the ion source [32−35], which can be seen in Fig. 10.

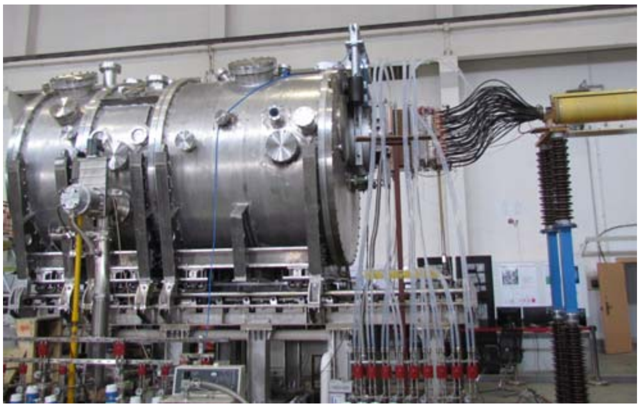

Fig.10 Picture of the ion source test bed

So far, five ion sources have been tested on the ion source test bed. Two ion sources were installed on the NBI-1, one is a backup source and two will be installed on the NBI-2.

Hydrogen is used on the ion source test bed because of the neutron radiation, while deuterium is used on the EAST-NBI. The performance of the ion source tested in the test bed with hydrogen is shown as follows.

The *I-V* characteristic of tungsten filaments of each ion source was tested. In general, the filament current can reach 3200 A with 32 filaments when 6.5-8.2 V are applied on the filaments. Each filament has 100 A current and can generate a high power plasma when the filament works in the emission limited mode. The arc voltage was regulated by the Langmuir probe and was typically 80-100 V. The typical beam current and arc current as a function can be seen in Fig. 11. The plasma generated in the arc chamber with arc current of 400-1100 A can deliver a 20-60 A ion beam. The optimum beam perseverance was investigated during the ion source tests, the optimum beam perseverance is 2.7 μP ($\mu\text{P}\equiv\text{A}/\text{V}^{3/2}\times10^6$) with a divergence angle of 1.2 degrees.

The beam fractions were measured with the Doppler Shift Spectroscopy (DSS) system. The lens was installed at the exit of the neutralizer cell. The deuterium beam fractions were measured on the EAST-NBI and the results are shown in Fig. 12. It can be seen that the proton ratio was increased with the increase of the beam energy. The powers of the neutral beam components of D(E), D(E/2) and D(E/3) are not easy to be measured directly. It can be estimated by the D^+:D_2^+:D_3^+ ratios, the neutralizer target density (neutralization efficiency) and the transmission. The energy per nuclear of the D(E/2) and D(E/3) is 1/2 and 1/3 of D(E), respectively. Considering that the nucleon number of D(E/2) and D(E/3) is two and three times that of D(E), the neutralization efficiency of D^+, D_2^+, D_3^+ and the transmission efficiency of D(E), D(E/2) and D(E/3) are similar (beam energy less than 80 keV). So, the power ratios of the neutral beam components of D(E), D(E/2) and D(E/3) are almost the same as the D^+:D_2^+:D_3^+ ratios.

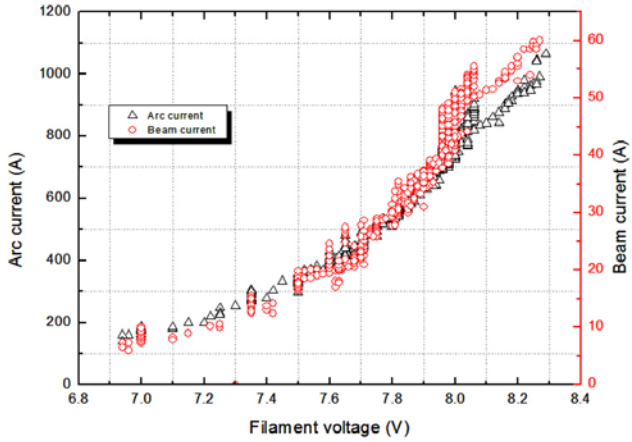

Fig.11 Arc and beam currents as a function of filament voltage

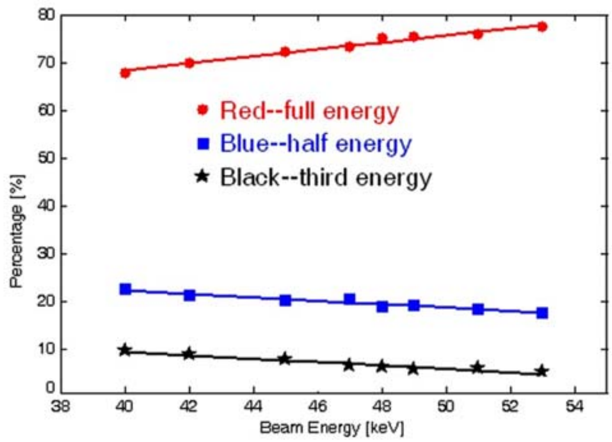

Fig.12 The deuterium beam fractions as a function of beam energy

Thermocouples were installed on the beam power deposition components, including the collimators, neutralizer, magnet pole shields, drift duct, ion dump, and calorimeter. They are used to monitor the temperature rise and to calculate the deposited beam power. The typical beam deposition on the NBI inner components was measured with beam energy of 50 keV and the results are shown in Fig. 13. An extracted ion beam power of 58 % was deposited on the calorimeter. The beam power loss on the duct collimator and drift duct was estimated as 1.3 % and 1.5 %, so the injected beam power can be estimated at about 55 %.

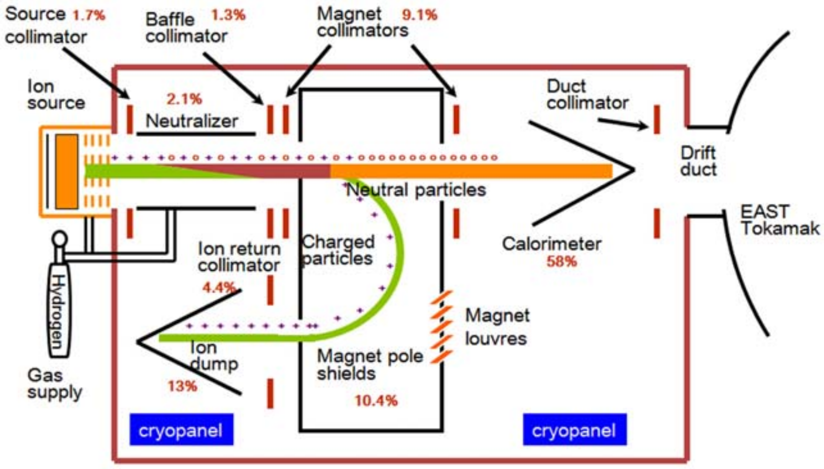

Fig.13 The beam power deposition on the NBI inner components

The beam profile was measured with the thermocouple installed in the back of plant of the calorimeter, typical results are shown in Fig. 14. The beam energy is 50 keV, ion beam power is 1.5 MW, beam perseverance is 2.76, and the beam divergence angle is 1.55 degrees.

The high beam power and long pulse operation of ion source was also tested in the test bed. A 4.8 MW hydrogen beam with beam energy of 85 keV was extracted, which can be seen in Fig. 15(a). The long pulse beam extraction needs to be modulated because of the high power deposited on the calorimeter. A 1.5 MW beam was extracted with a beam energy of 50 keV (shown in Fig. 15(b)). Because of high power deposited on the calorimeter, the beam needs to be modulated. The modulation frequency is 0.5 Hz with a duty ratio of 10%.

The NBI-1 was assembled on the EAST in September 2013 (shown in Fig. 16) and it injected its first neutral beam in July 2014. The H-mode plasma was achieved with NBI heating only with a deuterium neutral beam power of 1.7 MW.

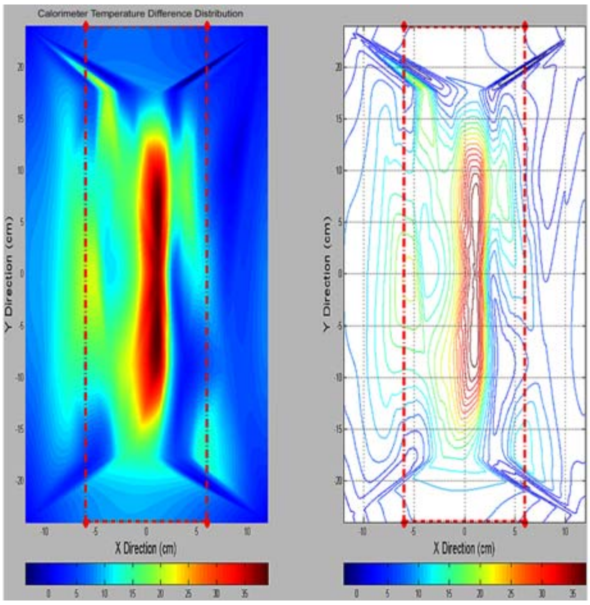

Fig.14 The beam profile on the calorimeter with beam divergence angle of 1.55 degrees

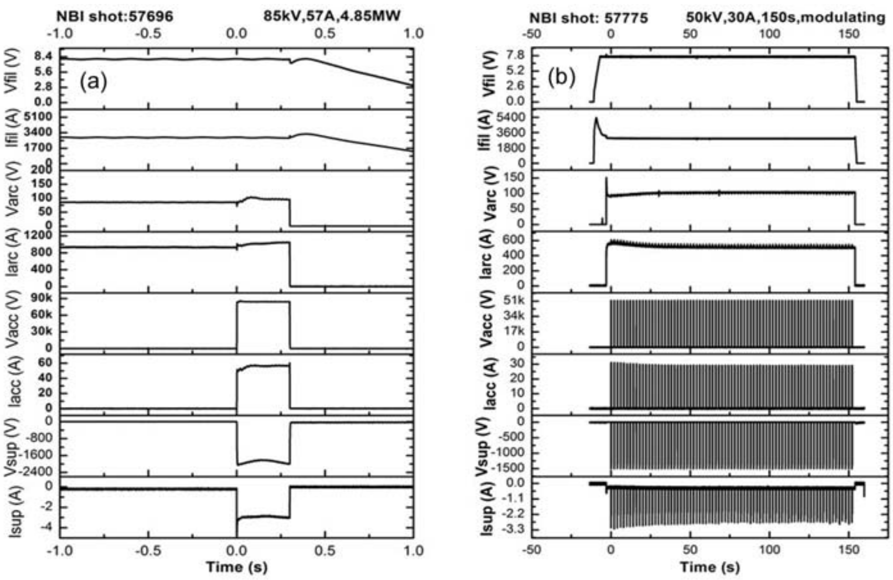

Fig.15 Waveforms of beam extraction of ion source on the test bed. (a) High power of 4.8 MW beam extraction, (b) Long pulse of 150 s modulated beam extraction with beam power of 1.5 MW

Fig.16 Picture of NBI-1 on the EAST experimental hall

The NBI was also used to maintain the long pulse H-mode plasma with other auxiliary plasma heating tools. A 22 s long pulse H-mode plasma was achieved with the NBI heating and the Low Hybrid Wave (LHW) heating. The two ion sources of the NBI alternately used an extract beam with 1 Hz frequency and 50% duty ratio. The injected beam power is about 0.6 MW for each ion source. In the summer campaign of the EAST physical experiment, the highest deuterium neutral beam power injected into the plasma was 2.6 MW with a beam energy of 63 keV.

The NBI-2 has a similar structure to NBI-1. The assembly of the NBI-2 is now finished, including the beamline support, the main vacuum chamber, and all of the inner components. The two ion sources for the NBI-2 have already finished being conditioned. They will be installed on the beamline at the end of April, and the integral tests of NBI-2 will follow.

4 Discussions and future plan

The EAST-NBI system delivered high power into the EAST plasma and achieved H-mode plasma. However, the beam power did not reach the designed power of 4 MW because the plasma density was not high enough. Besides, the injection efficiency of EAST-NBI system is about 68%, which also needs to be increased.

At present, the integral assembly of the NBI-2 in the port F is almost finished. In the near future, the NBI-2 will be tested and operated with NBI-1 on EAST plasma. The related research includes a plasma heating study with NBI-2 and two beamlines, a plasma rotation study, a neutron production study by two beamlines, a fast particles slowing-down time scale study, a plasma pre-ionization study with NBI, and a study of the plasma heating characteristics with NBI and other auxiliary heating tools.

5 Conclusions

The EAST-NBI system has successfully been developed in the ASIPP. An ion source test bed was developed for the ion source conditioning and optimization. In total, five hot cathode bucket ion sources were developed and tested on the ion source test bed, which individually achieve 4 MW beam power and long pulse operation with 100 s. The NBI-1 in the port of A on EAST has delivered a high neutral beam power of 2.6 MW and supports the H-mode plasma. The integral assembly of the NBI-2 in port F on the EAST will be completed at the end of April 2015. In the coming new campaign of the EAST experiment, the two beamlines will inject a high power neutral beam to heat and drive the EAST plasma. More results will be reported in the future.

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E-mail address of corresponding author XIE Yahong: xieyh@ipp.ac.cn