Design of Neutral Beam-Line of EAST*

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Abstract Neutral beam injector for EAST is designed to deliver deuterium beams with a power of 2 MW to 4 MW at an energy of 50 keV to 80 keV into the plasma with a beam dimension of 12 cm × 48 cm. Considering the beam generation and transmission, a columniform beam-line of Φ 250 cm × 400 cm is designed with a neutralizer, ion dump, calorimeter, bending magnet and cryopanels. The arrangement of the internal elements for the beam-line is reported. A rectangular sleeve coupled to the ion source is employed as the neutralizer. At the downstream of the neutralizer, a dipole magnet separates the residual ions from the beam passage with a reflection radius of 42 cm for the full energy particles. The calorimeter and the ion dump serve as high heat flux components, which will work as thermal inertia targets in the first phase of operation.

Keywords: neutral beam, experimental advanced superconducting tokamak (EAST), beam-line

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1 Introduction

In EAST the first plasma discharge was achieved successfully in 2006 [1]. In order to carry out the study in steady-state advanced tokamak operational mode, a neutral beam (NB) injection system is being built up with two injectors at an energy of 50 keV to 80 keV and with a beam power of 4 MW [2] for each, as shown in Fig. 1.

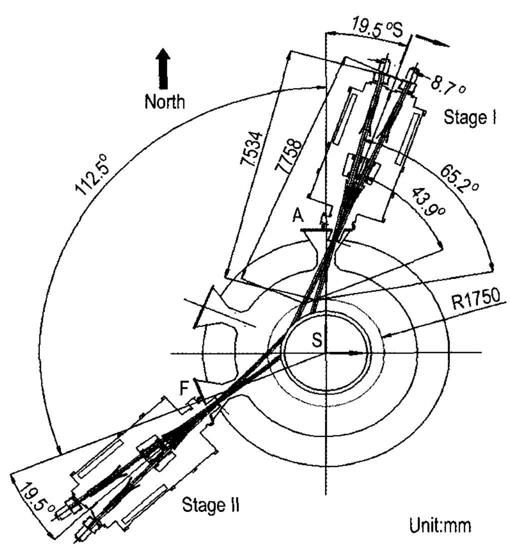

Fig.1 Layout of the two injectors on EAST

Heating with NB injection has been successfully adopted in different magnetic fusion devices [3,4]. It is verified that NB injection is one of the major methods to heat plasma to the ignition temperatures. For the NB heating, the neutrals injected into tokamak are ionized inside the plasma by charge exchange and collisions with both electrons and ions [5]. Then, the fast ions generated are confined by the magnetic field of the tokamak and deliver their energy to plasma particles through collisions.

The generation of neutral beams for a magnetic fusion study includes three stages, namely generation of an ion beam, neutralization of the ion beam, separation and treatment of residual ion [6], as shown in Fig. 2. The generation of an ion beam is achieved via electrostatic extraction and acceleration of the ions to the desired energy. The rest process known as beam transport will be carried out in the beam-line, the vacuum vessel with the neutralizer, reflection magnet, high heat flux elements, cryopumping and so on.

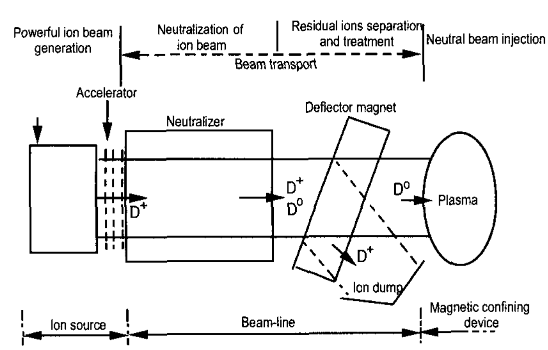

Fig.2 Block diagram of the neutral beam injector

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2 Principle of NB transport and design for the key elements in beam-line

For the deuterium beam at an energy of 80 keV, the positive ion source is more cost-effective for the operation. So an arc-discharge positive ion source is selected for the neutral beam injector in EAST. The ion beam generated should be neutralized to form a neutral beam capable of penetrating the confining magnetic field. Neutralization of the ion beam, separation and treatment of the residual ions are the main processes in NB transport. Consequently, the reflection magnet and the neutralizer, as two key elements, play a crucial role in beam transmission efficiency, which will be described below.

2.1 Neutralizer

The neutralizer is applied to make the positive ion capturing an electron and hence forming an energetic atom. Usually, as the ion beam is passing through a charge exchange target, some energetic ions can capture electrons by electron-capturing collision. At the same time, the molecular ions will be excited by collisions and get dissociated. Generally, after passing the neutralizer, there are just D^{o} and D^{+} with full energy (E), half energy ($E/2$) and one third of energy ($E/3$) [7,8]. In our case by considering the cost of neutralization and the feasibility of the project, a gaseous charge exchange target is chosen for the NB injector of EAST.

There are two competitive processes in the neutralizer, namely charge exchange and ionization. In the neutralizer, atomic processes involving charge transfer and dissociation will change the particles' charge state and momentum. Thus, these processes will determine the species evolution along the neutralizer downstream and the neutralization efficiency. Numerical calculations provided detailed information about the species evolution [9]. This study was based on the following sets of equations (DE) for relevant species:

D^{+} beam:

$$\frac{\mathrm{d}F_i}{\mathrm{d}\pi}=\sum_{j\neq i}F_j\sigma_{j,i}-F_i\sum_{j\neq i}\sigma_{i,j},\ \ i,j=\mathrm{D}^+,\ \mathrm{D}^0,\ \mathrm{D}^-. \tag{1}$$

D_2^{+} beam:

$$\frac{\mathrm{d}F_k}{\mathrm{d}\pi}=F_l\sigma_{l,k}-F_k\left(\sigma_{k,l}+\frac{1}{2}\sum_i\sigma_{k,i}\right),\ \ k,l=\mathrm{D}_2^+,\ \mathrm{D}_2^0; \tag{2}$$

$$\frac{\mathrm{d}F_i}{\mathrm{d}\pi}=\sum_{j\neq i}F_j\sigma_{j,i}-F_i\sum_{j\neq i}\sigma_{i,j}+\sum_k F_k\sigma_{k,i},\quad i,j=\mathrm{D}^+,\ \mathrm{D}^0,\ \mathrm{D}^-. \tag{3}$$

D_3^{+} beam:

$$\frac{\mathrm{d}F_{\mathrm{D}_3^+}}{\mathrm{d}\pi}=-F_{\mathrm{D}_3^+}\left(\frac{1}{3}\sum_i\sigma_{\mathrm{D}_3^+,i}+\frac{2}{3}\sum_k\sigma_{\mathrm{D}_3^+,k}\right); \tag{4}$$

$$\frac{\mathrm{d}F_k}{\mathrm{d}\pi}=F_l\sigma_{l,k}-F_k\left(\sigma_{k,l}+\frac{1}{2}\sum_i\sigma_{k,i}\right)+F_{\mathrm{D}_3^+}\sigma_{\mathrm{D}_3^+,k},\quad k,l=\mathrm{D}_2^+,\ \mathrm{D}_2^0; \tag{5}$$

$$\frac{\mathrm{d}F_i}{\mathrm{d}\pi}=\sum_{j\neq i}F_j\sigma_{j,i}-F_i\sum_{j\neq i}\sigma_{i,j}+\sum_k F_k\sigma_{k,i}+F_{\mathrm{D}_3^+}\sigma_{\mathrm{D}_3^+,i},\quad i,j=\mathrm{D}^+,\ \mathrm{D}^0,\ \mathrm{D}^-; \tag{6}$$

where F is the fraction of particle species in the beam, σ is the collision cross-section, and π is the line density of target gas (i.e., target thickness) in the neutralizer. With an estimation from the formula, the target thickness in the neutralizer for the EAST-NBI is about $3\sim9\times10^{15}$ cm^{-2}. A model of the neutralizer structure is shown in Fig. 3. Generally, the pressure at the exit of the accelerator is 0.05 Pa, the pressure at the end of the neutralizer is about 0.03 Pa, and the base pressure in the vacuum is 0.01 Pa. According to the equation of state for ideal gas and the formula for the target gas, the relation between the pressure at the entrance of the gas inlet and the target thickness in the neutralizer can be expressed as

$$f(P,l)=\int_0^{70}10^{-6}\times\frac{\left[0.05-x\left(\frac{0.05-P}{70}\right)\right]\times N_A}{RT}\mathrm{d}x+\int_0^{l}10^{-6}\times\frac{\left[P-x\left(\frac{P-0.03}{l}\right)\right]N_A}{RT}\mathrm{d}x+\int_0^{200-l}10^{-6}\times\frac{0.01\times N_A}{RT}\mathrm{d}x. \tag{7}$$

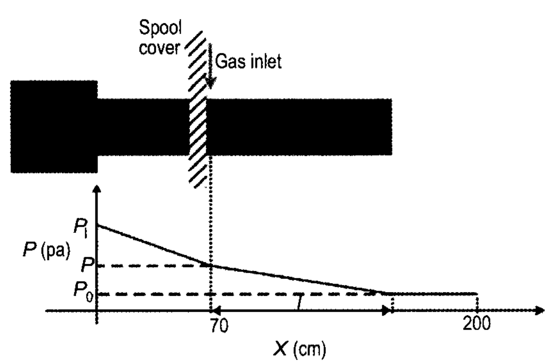

Fig.3 Model for the neutralizer structure

As shown in Fig. 4, for a neutralizer's length of 90 cm and a drift duct between the ion source and neutralizer of 70 cm, which will work partly as a neutralizer, in order to meet the requirement for the target thickness, the pressure at the entrance of the gas inlet should be up to 0.5 Pa.

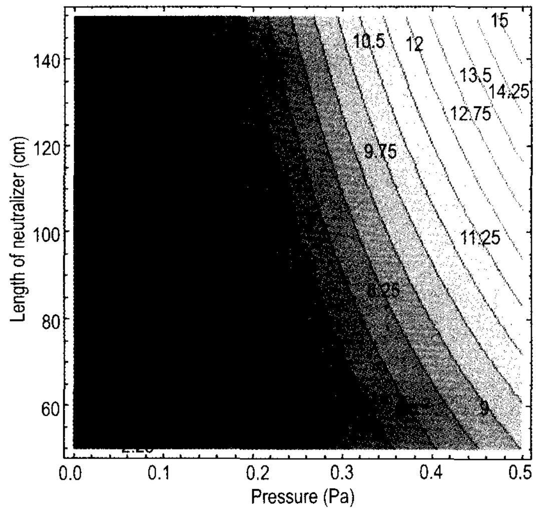

Fig.4 Contour of the function of target thickness

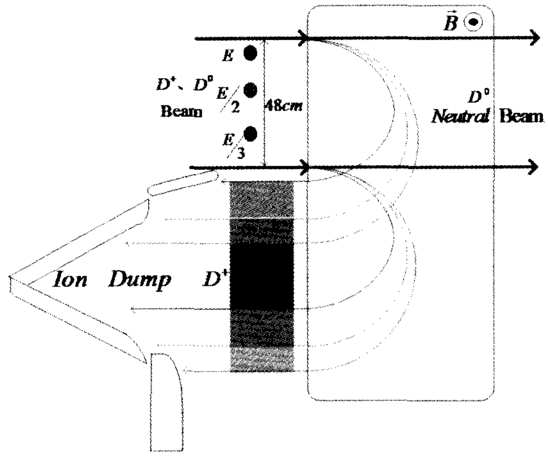

Fig.5 Particle track in the bending magnet region

2.2 Design for reflection magnet

Emerging from the neutralizer, there will be a combination of beams with energetic atoms and energetic ions. At the downstream of the neutralizer, the non-neutralized ions, called residual ions, carry a considerable amount of power. Since the residual ions would be deflected due to the stray magnetic field around tokamak in an uncontrolled manner and would cause significant damage to the device through a thermal overload [6,7], it is necessary to remove the residual ions before the beam arrives at the aperture. Generally both magnetic field and electric field can be applied for residual ion separation. Considering the cost of the device for residual ion separation, the vacuum distribution in the beam-line and the additional gas source due to residual ion deposition, a 180° -reflection magnet is chosen for the NB injector in EAST. At the downstream of the residual ion beam, a "V" shaped ion dump is designed for residual ion treatment [10,11]. The orbits of particles with full energy, half energy and one third of energy are shown in Fig. 5. The reflection magnet makes the residual ions deviating from the beam passage, due to the gyro-motion of ions in a magnetic field. The bending radius can be written as

$$R = \frac{\sqrt{2mE}}{qB}, \tag{8}$$

with q the charge of the ion, m the mass of the particle, E the kinetic energy of the ion and B the magnetic field. Under the same magnetic field, the ratio of the bending radius for ions with different energy can be given by,

$$R_E : R_{E/2} : R_{E/3} = \sqrt{6} : \sqrt{3} : \sqrt{2}. \tag{9}$$

In our case, in order to separate the residual ions completely from the beam path, the radius for particles with one-third energy must be larger than 24 cm. Thus, the radius for full-energy particle is about 42 cm. As is shown in Fig. 6, the reflection radius for ions with the energy of 80 keV in a magnetic field of 1376 Gs is

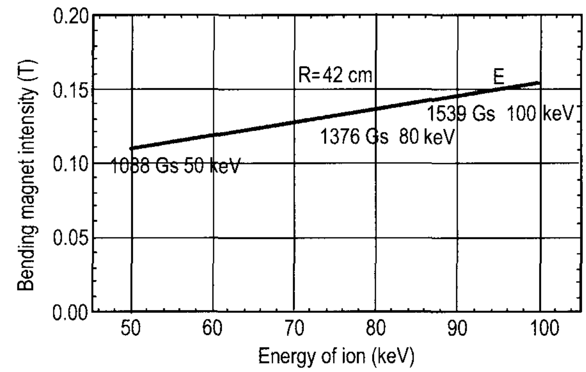

Fig.6 Dependence of the bending magnetic field upon the energy of deuterium ion

42 cm. Considering the upgrade of beam energy and the safety requirements in engineering, an 'H' type dipole magnet should be designed for a uniform magnetic field of 1900 Gs.

According to Ampere's law, the excitation ampere turns to produce the required magnetic field can be expressed as

$$NI = \oint H \cdot \mathrm{d}l = \oint_{L\mathrm{air}} \frac{B}{\mu_0}\mathrm{d}l + \int_{L\mathrm{iron}} \frac{B}{\mu}\mathrm{d}l$$

$$= \frac{B}{\mu_0}L_{\mathrm{air}} + \frac{B}{\mu_0}L_{\mathrm{iron}}\left(\frac{\mu_0}{\mu_{\mathrm{iron}}}\right), \tag{10}$$

with μ_0 the permeability in vacuum and μ_{iron} the permeability of the pole and the magnet core. When the magnet core is not saturated, μ_{iron} is approximately constant and is much larger than the permeability of the vacuum, i.e., $\mu_{\mathrm{iron}} >> \mu_0$. So, Eq. (10) can be simplified to be

$$NI \approx L_{\mathrm{air}}B \Big/ \mu_0, \tag{11}$$

with B in $\mathrm{Wb/m^2}$ and L_{air} in meter. For an H-type solenoid dipole, L_{air} is the distance of the poles. For the NB injector in EAST, considering the beam divergence, the gap of the reflection magnet should be of longer than 20 cm, i.e., $L_{\rm air}$=20 cm. Then, the designed number for ampere-turn is about 33,500. From a view in electrical engineering, the current density for external water-cooled wire is about 3 A/mm^2, and the current density for internal water-cooled wire is about 10 A/mm^2. The area of section for the coil is thus 11,166 mm^2, 3,350 mm^2 for external and internal water-cooling, respectively. The internal water-cooled coil with 64 turns is employed for the NB injector in ESAT.

For a reflection radius r_m of 42 cm, according to the empirical formula for the available coefficient for the poles ξ, one has $\xi = \frac{r_m}{R}$, with $\xi = 0.78 \sim 0.91$ generally, with R the radius of the magnet pole. For an 180°-reflection magnet with an entry of 90° and an exit of 90°, a rectangular cross section is adopted for the magnet pole. In order to adjust the radius of ion deflection, the size of the magnet pole section is set about 140 cm × 50 cm.

For the treatment of the residual ions, a "V" shaped ion dump is designed. Since the beam profile is of a Gaussian-like, there are two bending angles for the ion dump plane, which can use the whole space of the ion dump. This type of residual ion dump was demonstrated in other NB injectors. Compared to the electrostatic residual ion dump, plasma formation in the reflection region would not occur for this type of ion dump. Matching the requirement of the steady-state operation, the length of ion dump is up to 1 m for the NB injector in EAST.

3 Arrangement of beam-line and system specification

In order to enable the NB injector to work independently of the plasma in tokamak, the beam-line calorimeter is designed downstream just of the bending magnet. The calorimeter is a "V" shaped water-cooled component with high heat flux. Due to a limited space, the length of beam-line for the calorimeter is about 80 cm for the NB injector in EAST.

In addition, together with the residual gas of the charge exchange target and the ion source, there is a considerable flow of cold neutral gas from the neutralizer. An estimation of the typical parameters for the NB injector in EAST indicates that the rate for diffused gas from the neutralizer is approximately 4.9 Pa·m^3/s in deuterium. In addition, the beam ions, thermalized in the ion dump and collimator, contribute a rate of 1.0 Pa·m^3/s after recombination [12]. The gas may cause an intrusion of impurity to the tokamak plasma and a re-ionization of energetic atoms. This effect can even lead to a loss in beam power or complete beam blocking. To avoid it, a pressure below 10^{-2} Pa should be maintained in the injection system, with a rough estimate. A gas flow of about 10 Pa·m^3/s thus requires a pumping rate of several mega liters per second. According to the state of the art, only the cryopanel can provide such a pumping rate. For the NB-line in EAST, two cryopanels are designed as two parts with a total surface area of 14 m^2.

In EAST a NB power of 4 MW is delivered from two ion sources and the beam transport is located in vacuum vessel. Two unattached beam passages are chosen for easy maintenance and operation. In order to get a maximum angle of the tangential injection, two beams are focused at the injection port through an angle of 8.6°. The overall length of beam-line is about 6 m, from the exit grid to the center of the tokamak plasma. The estimated weight of the beam-line is about 40 tons. The central line of beam is 6.18 m above the ground floor, the same height as the equatorial plane for EAST.

According to the above design, the beam-line consists of neutralizer, reflection magnet, ion dump, calorimeter and cryopumping, which are called internal elements and installed in a vacuum vessel. The vessel is columniform one of Φ250 cm × 400 cm and divided into three parts. The rear cryopanel, neutralizer and ion dump are installed in the first part, the reflecting magnet is installed in the second part and the front cryopanel and calorimeter are installed in the third part [10,13], as shown in Fig. 7. In addition, several collimators are fixed at the entrance and exit of the neutralizer and the reflection magnet. The front cryopanel is of a circular disk shape with a large rectangular window cut out of the center for the calorimeter, and the rear cylindrical cryopanel is coaxial with the beam-line vessel. At the same time, a gas baffle is employed, located between the neutralizer and the reflection magnet to form an optimal vacuum distribution. Thus, the beam-line vacuum vessel is roughly divided into three differentially pumped chambers by a gas baffle and a reflection magnet.

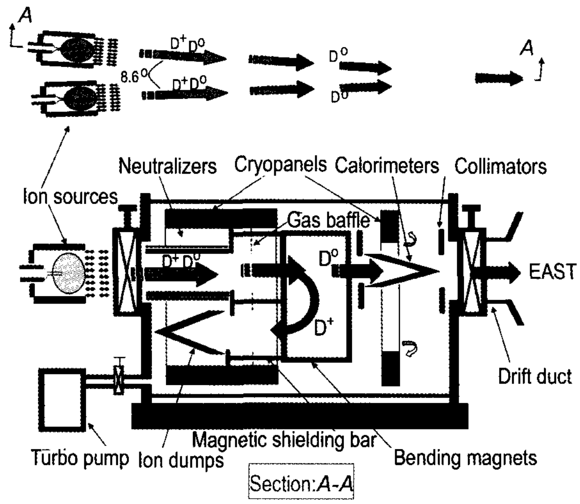

Fig.7 Arrangement of the beam-line

An overall specifications for the beam-line is listed in Table 1. The neutralization rate of 80 keV D$^+$ is about 65% in a simple charge exchange gas target. The reflection magnet can supply a magnetic field suitable to match the bending radius at 42 cm. In the second operational phase, the system would work for a period of 100 s.

Table 1. Main parameters of the beam-line

NO.	Parameter name	Quantity
1	Length of drift duct between ion source and neutralizer	70 cm
2	Length of the neutralizer	90 cm
3	Magnetic field strength	0∼1900 Gs
4	Deflection radius (E)	42 cm
5	Area of front cryopanel	6 m^2
6	Area of rear cryopanel	8 m^2
7	Area of ion dump	≈ 3.2 m^2
8	Area of calorimeter	≈ 1.5 m^2
9	Beam energy	50∼80 keV
10	Beam power	2∼4 MW
11	Ion source number in one beam-line	2
12	Duration time	10∼100 s

4 Conclusion

The neutral beam has been used in different ways as the auxiliary heating on magnetically confined plasmas. The NB system in EAST will provide a neutral beam of 4 MW for both heating and current drive in plasma. Because of the limited injection angle in EAST, and in order to minimize costs, each injector is mainly made up of two unattached ion sources and one beam-line. The beam-line possesses two independent beam passages. The neutralizer, reflection magnet, ion dump, calorimeter and cryopumping are installed in the vacuum vessel to carry out beam neutralization, residual ion separation and treatment.

References

1 Gao X, Li J, Wan B, et al. 2007, Nucl. Fusion, 47: 1353

2 Hu C D, Xie Y L, Xie Y H. 2009, Development of Long Pulse Neutral Beam Injector System for the EAST Tokamak. Presented at the 2009 Annual CNS Conference (Beijing, China, 2009), Chinese Nuclear Society, Beijing, China

3 Wesson J. 1997, Tokamaks. 2nd ed., Oxford Clarendon Press, Oxford, UK

4 Gibson G, Lamb W, Lauer E. 1959, Physical Review, 4: 937

5 Hu C D, Xie Y H, Liu S, et al. 2010, Plasma Sci. Technol., 12: 571

6 Speth E. 1989, Rep. Prog. Phys., 52: 57

7 Liang L Z, Hu C D, Liu Z M, et al. 2008, High Power Laser and Particle Beams, 20: 849 (in Chinese)

8 Hanada M, Kashiwagi M, Inoue T, et al. 2004, Rev. Sci. Instrum., 75: 1813

9 Kim J, Haselton H H. 1979, J. Appl. Phys., 50: 3802

10 Cordier J J, Hemsworth R, Chantant M, et al. 2005, Fus. Eng. Des., 74: 397

11 Hall D D, Mudawar I. 1999, Inte. Journal of Heat and Mass Transfer, 42: 1429

12 Hu C D, NBI Team. 2009, EAST neutral beam injector physical design. Serial No. 09013007, Technical Report, Institute of Plasma Physics, the Chinese Academy of Sciences, Hefei, China

13 Colleraine A P, Doll D.W., Holland M M, et al. 1978, A Parametric Study of the Doublet III Neutral Beam Injection System. Presented at the 10th Symposium on Fusion Technology. Padova, Italy, Sep. 1978

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