Conceptual Design of Confined Alpha Particle Diagnostic System for ITER Using an Energetic He^0 Beam

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A conceptual design of an active-neutral-beam-probe-diagnostic-system for alpha particles produced by D-T nuclear reaction in a plasma confined by a magnetic fusion reactor has been examined. An energetic He^0 beam plays an important role in the system. To detect a signal of neutralized alpha particles from the fusion plasma with enough S/N ratios, a high brightness He^0 beam produced by spontaneous electron detachment from He^- ions is required. A prototype of a He^+ ion source has been designed and assembled to test the performance in producing a source beam for high intensity He^- beam through a double-charge-exchange process in alkali metal vapor.

1. Introduction

In the next generation magnetically confined fusion experimental reactors, such as ITER (International Thermonuclear Experimental Reactor), plasmas will be self-heated by high-energy alpha particles produced by D-T nuclear fusion reaction. The spatial and energy distributions of alpha particles in the core plasma are one of the most important issues for burning plasma diagnostics. Several methods to measure the velocity distribution of alpha particles have been proposed. One of the most promising methods is based upon the double-charge-exchange reaction of a fusion produced alpha particle in a core plasma to capture two electrons to escape from the plasma and detected by an energy analyzer installed outside the confined magnetic field. Post *et al.* proposed an active beam probe method to neutralize the alpha particles by injecting an energetic neutral helium (He^0) beam into the core plasma.[1] Sasao and Sato showed the possibility of producing an energetic ground state He^0 beam by spontaneous electron detachment from negative helium ions (He^-) to diminish impurities of the metastable states of He^0.[2]

In this paper, a conceptual design of the measurement system of the velocity distribution function of alpha particles in the core plasma using an energetic He^0 beam

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with a neutral particle energy analyzer is shown. In section 2, a measurement scheme is described. The counting rate of the neutralized alpha particles produced by double charge exchange reaction due to incident energetic He^0 beam is estimated taking into account of the beam attenuation in the plasma. In section 3, the measurement system employing the active probing beam with the energy analyzer for the neutralized alpha particles is described. Components of the system are listed, and specifications of a high intensity He^+ ion source with three concave multi-aperture electrodes are described.

2. Measurement scheme

Sasao *et al.* described the diagnostic beam system for alpha particle measurement on ITER previously.[3] However, the system should be modified to be adaptable to the new ITER design. A schematic illustration of a possible geometry for tangential injection of an energetic probing beam into ITER plasma is shown in Fig.1. Fusion produced alpha particles after being neutralized by the injected beam are detected by the energy analyzer installed outside of the plasma confining magnets. With this configuration, the detector can cover the entire region of radial position in the plasma.

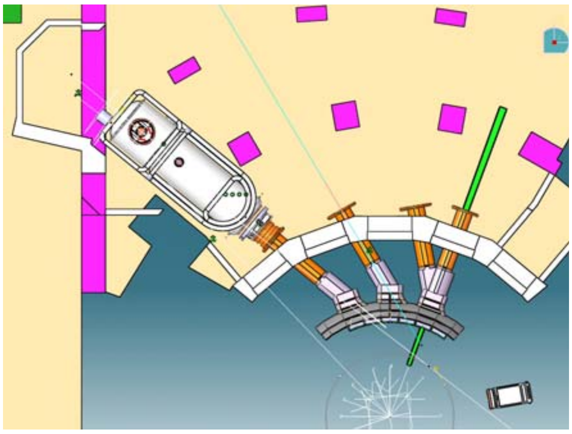

Fig. 1 Schematic illustration of a possible geometry of tangential injection of an energetic He^0 probing beam into ITER plasma. Diagnostic NBI system is left-up side behind the third NBI heating system and the energy analyzer is installed right-down side in the figure.

In the previous report [3], the velocity of the He^0 beam is required to exceed $0.6v_\alpha$, where v_α is the velocity of the fusion alpha particle at its birth. This velocity was considered necessary for the incident beam to penetrate to the center of the plasma. The number of neutralized alpha particles per a velocity interval, $C(v)dv$, is derived by,

$$C(v)dv = \eta(v)n_a(v,r)n_b(r)\sigma_{20}(v)v_{rel}Vd\Omega dv,$$

where $\eta(v)$, $n_\alpha(v,r)$, $n_b(r)$, $\sigma_{20}(v)$, v_{rel}, V are transmission coefficient of outgoing neutralized alpha particle, local density of alpha particles, that of beam particles, cross-section of two electron capture of alpha particles, relative velocity between an alpha particle and an injected neutral particle, plasma volume respectively. The charge-exchange cross-section decreases rapidly when the relative energy is greater than 200 keV.[4] The total counting rate for an ITER plasma of $n_e(r=0) = 10^{20}$ m^{-3} with 1% produced alpha particle density and 10% attenuation of He^0 beam with the velocity of $0.8v_\alpha$, the atomic current of 10 mA in the area of 200 mm × 50 mm is estimated to be 10^5-10^6 particles per second.

3. Active beam probe system using He^0 beam

In order to diagnose the velocity distribution of the alpha particles produced by D-T nuclear fusion reaction, an active beam probe system using He^0 beam with an energy analyzer has been designed as shown in Fig. 1. In the conceptual design, the system consists of a high-brightness positive helium (He^+) ion source, an alkali-metal vapor cell to produce He^- ions by double charge exchange reaction, a magnetic deflection type ion separator with a stigmatic beam focusing, an electrostatic pre-accelerator, a radio-frequency quadrupole (RFQ) linac, a long-free-flight beam transport line and a neutralized alpha particle detector. The ion beam production and acceleration devices are designed to be installed behind the third neutral beam injection (NBI) heating system. The schematic diagram of the He- beam production and acceleration devices is shown in Fig. 2. The accelerated He^- beam is injected into the beam transport line of the NBI heating system and the neutralized He^0 beam produced by auto-detachment process during the long beam transport line is directed to the fusion reactor. The element species, the beam energy and the beam current in each component are tabulated in Table 1. The efficiency for the double charge exchange from He^+ to He^- is referred in Ref. [5] and the lifetime of He^- is referred in Ref. [6] which is recently measured by utilizing an electrostatic ion storage ring.

Table 1 Element species, beam energy and current in each component (expected values).

	Exit of He^+ ion source	Exit of alkali metal vapor cell	Downstream of ion separation	Exit of Electrostatic Accelerator	Exit of RFQ linac	Downstream of 40 m free flight tube
Element	He^+	He^+, He^0, He^-	He^-	He^-	He^-	He^0
Energy	10-30 keV	10-30 keV	10-30 keV	~200 keV	~ 2 MeV	~ 2 MeV
Current	3 A	3 A (total)	~60 mA	~55 mA	~ 50 mA	~ 10 mA

There have been many investigations on the production of a high-intensity He^- beam in accelerator applications. The most reliable method is to employ double-charge-exchange reaction of a He^+ beam in an alkali metal vapor.[7],[8] A high intensity He^+ ion source is required to produce enough intensity of He^- beam with a low divergence. At National Institute of Advanced Industrial Science and Technology, an ion source with three concave multi-aperture extraction electrodes to converge the formed beam into a narrow spot has been developed.[9] A He^+ beam extracted from this type of ion source injected into an alkali metal vapor cell will produce a high intensity He^- beam. A prototype of the He^+ ion source based on this idea has been designed. The specifications of the He^+ ion source are tabulated in Table 2.

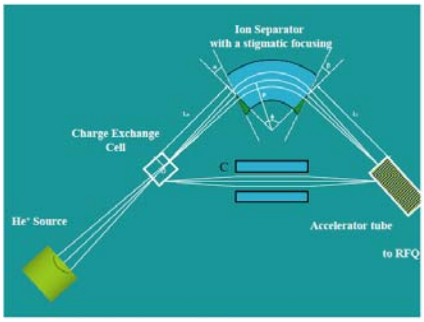

Fig. 2 Schematic diagram of He^- beam production and acceleration devices.

Table 2 Specifications of He^+ ion source.

Beam Current	3 A
Beam Energy	10-30 keV
Beam Divergence	< 1.0 deg.
Extraction Range	100 mm in diameter
Focal Length of the Concave Electrodes	750 mm

Meanwhile, a proof-of-principle low beam current test stand is also under construction to check necessary components for the active beam probe system and to investigate the beam qualities.[10]

4. Summary and future plans

A conceptual design of confined alpha particle diagnostic system for ITER using an energetic He^0 beam produced from auto-detachment of an electron from He^- ions has been described. In the system, the energy analyzer can detect the neutralized alpha particles distributed the entire region of radial position in the plasma. In order to obtain the signal with enough S/N ratio detection, the injected energetic He^0 beam is required to possess the intensity of about 10^{15} particles per second.

The prototype of the He^+ ion source for producing the high intensity He^- beam by double-charge-exchange reaction will be assembled in 2006 spring at National Institute for Fusion Science in Japan, where a high technology for neutral beam heating has been developed. The beam quality of the high brightness He^+ beam will be investigated.

Further development of the acceleration and neutralization of He^- beam is desired. Especially, RFQ acceleration of the high intensity He^- beam up to 2MeV is one of the most challenging subjects. It is also necessary to survey the possibility of neutralization of He^- beam by photo-detachment process in order to replace the long beam transport line for electron auto-detachment process to a short high efficiency photo-neutralizer.

Acknowledgements

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