1. Introduction

Nuclear fusion is considered as one of alternative future energy resources and its research has been vigorously performed in the wold. The advantage of nuclear fusion over conventional energy resources (coal, oil and natural gas, or nuclear fission) is that principal fuel, deuterium (which is extracted from water) and tritium (which does not occur naturally, but can be obtained from nuclear breeding in lithium), are plentiful resource. Furthermore, unlike fission, fusion reaction produce no long-lived radioactive nuclides and a reactor will be inherently safe in operation: the loss of reactor control will naturally extinguish the reactions.

Until now, several schemes of magnetic plasma confinement and inertial confinement devices have been investigated. In the magnetic plasma confinement devices, the most employed and concentrated device is "Tokamak" [1]. The tokamak is a device of axisymmetric toroidal geometry. The largest toroidal magnetic confinement device built at the Kurchatov Institute in the 1960s was the T-3 tokamak. Recently, in particular, performance improvement in every aspect is made in three large tokamaks: TFTR at the Princeton Plasma Physics Laboratory (shut down in 1997), JET at the Culham Laboratories in the UK and JT-60U at Naka Fusion Research Establishment of JAERI in Japan. The break-even plasma condition has been achieved in JET [2] and JT-60U [3]. The deuterium-tritium mixture discharges have been performed in TFTR [4] and JET [5]. JET has successfully produced fusion powers up to 16 MW. As the next major step in tokamak fusion research, International Thermonuclear Experimental Reactor (ITER) project is being designed under international collaboration [6].

The purpose of ITER is to realize plasma parameter such as temperature and density of the level equal to the nuclear fusion reactor. That is to say, it is to do long-time burning high power using the real fuel of Tritium and Deuterium. The principal physics goals of ITER are:

i. To achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary heating power (Q) of at least 10 for a range of operating scenarios and with a duration sufficient to achieve stationary conditions on the timescales characteristic of plasma processes;

ii. To aim at demonstrating steady-state operation using non-inductive current drive with a ratio of fusion power to input power for current drive (Q) of at least 5.

The success of ITER project will provide the next major step for the advancement of fusion science and technology, and is the key element in the strategy to reach the following demonstration electricity-generating power plant (DEMO) in a single experimental step. Therefore ITER project is very important.

In order to develop the nuclear fusion study further, a self-ignition due to the heating by alpha-particle generated by Deuterium-Tritium (D-T) fusion reaction, so called 'alpha-particle heating', and its maintain for long time are important objectives. Fast 3.5 MeV alpha particles are indispensable to a source of plasma heating in fusion core plasmas and confinement of alpha particles is very important.

However, for core plasma of the temperature of about 10keV with Maxwell velocity distribution function, such alpha particles form the peak of velocity distribution function in high energy side which deviates from the Maxwell distribution. Therefore various instabilities can be excited due to interaction between fast alpha particles and MHD oscillation. For fast alpha particles produced by D-T reaction, it was predicted by Rousenbluth et al. [7] in 1975 that Alfvén wave could be excited by the mechanism of inverse Landau damping, which kinetic energy of alpha particles transfer wave energy of Alfvén wave, when their velocity is comparable with Alfvén velocity in the process of slowing down by collision with main plasma. After that, it was realized by C. Z. Cheng et al. [8, 9] that Alfvén eigenmode (AE) could be a serious threat to good classical confinement of energetic alpha particles in a tokamak and, hence to the achievement of ignition in a next step device such as ITER.

Therefore, significant progress has been achieved in the development of theory and in dedicated experimental study of AEs in present day machines like TFTR, JET, DIII-D and JT-60U. The various AEs were observed and identified in experiments and simulated numerically with an impressive degree of detail.

Toroidicity causes the continuous frequency spectrum of shear Alfvén waves in a tokamak plasma to exhibit "a radial gap". Within this gap discrete frequency modes, called *Troidicity-induced Alfvén eigenmodes* (TAEs) [8, 9] can be existed. Whereas the shear Alfven wave of the continuum are strongly damped, TAE can be destabilized by fast ion without receiving the damping by the Alfvén resonance due to continuous spectrum, since it exists in the spectrum gap. The growth rate of TAE induced by fast ion was calculated by Fu et al. [10]. The result indicate TAEs in the burning plasma with a high alpha particle pressure gradient are destabilized due to overcoming several stabilization mechanisms such as continuum damping [11-14] and radiative damping [15], ion Landau damping [16], electron Landau damping [17], and trapped electron collisional damping [18 19]. This paper gave the strong motive in which the TAE excitation experiment was promoted in the large tokamak under work.

TAEs were first observed experimentally in TFTR in using neutral beam injection to provide the first ion [20]. These experiments were performed in low toroidal magnetic field (~ 1T) and high electron density to make the velocity of the injected beam ions nearly Alfvén velocity. After that, similar experiments in DIII-D were performed, TAEs then were observed [21]. It was worthy of notice that about 50% loss of injected fast beam ions in the TFTR and 70% loss in DIII-D were observed in these experiments.

TAEs are also observed with hydrogen minority energetic tail ions due to ion cyclotron resonant heating in JT-60U [22 23], TFTR [24 25] and JET [26]. In JT-60U, TAEs were destabilized by hydrogen minority tail ions with an energy of several MeV. These TAEs expelled up to 70% of the fast ions with energy 2.5 MeV from the plasma.

While the first observation of TAEs purely driven by alpha particles was made in

TFTR DT experiments, but only in discharge with high q(0) and weak magnetic shear, and only after (~100ms) the neutral beam heating was turned off [27].

As mentioned above, TAE studies in several tokamaks were performed. However, only a limited parameter domain in the $v_{b//} / v_A$ (the ratio of parallel beam ion velocity to the Alfvén velocity) and $\langle\beta_h\rangle$ (volume averaged hot ion β) space has been studied so far. TAEs excited by alpha particles in TFTR experiments were studied with low $\langle\beta_h\rangle$. While, at high $\langle\beta_h\rangle$, chirping TAEs excited by fast beam ions were observed in DⅢ-D[28] as shown in Fig.1.1.

Recently, in JT-60U the ITER relevant parameter regime of $0.1\% < \langle\beta_h\rangle < 1\%$ and $v_{b//} / v_A \sim 1$ has been studied recently with the Negative-ion-based Neutral Beam (N-NB) of $E_{beam} \geq 360$ keV in order to assess the AE activity and the effect of AEs on the loss of energetic ions [29] as shown in Fig.1.1. Bursting modes called Fast Frequency Sweeping (FS) mode and Abrupt Large-amplitude Event (ALE) in the frequency range of the TAEs were observed [29, 30] so far.

Since the alpha particle birth domain in ITER burning plasmas can be explored, TAE experiment using N-NB in JT-60U is important. In this thesis, the study of fast ion transport is performed in N-NB injected plasmas.

In the study of TAEs, it is important to study effect of TAE instabilities on the confinement of energetic beam ions for the assessment of alpha-particle transport in ITER. In order to do this, measured neutron emissions have been used on DIII-D, TFTR, and JT-60U. Neutron measurements are very useful tool to investigate the fast ion behavior since neutron emission rate depends on the behavior of fast ions. In case of the TFTR experiment which observed TAE using NBI first, neutron emission rate was reduced 7 % at most by the occurrence of burst-type TAEs and the transport of beam ions from center region was observed at first [20]. In DIII-D, the reduction rate of the neutron

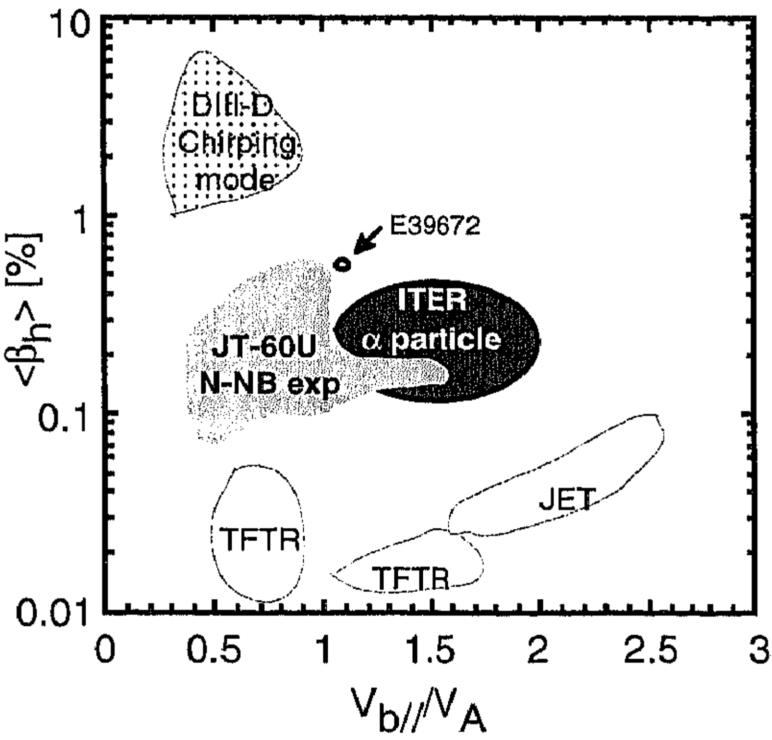

Figure 1.1 *Parameter domains in* $<\beta_h>$ *and* $V_{b//}/V_A$ *space of Alfven Eigenmode experiments performed in large tokamaks. Fast ions domain of JT-60U experiment using N-NB, DIII-D experiment with chirping modes, TFTR experiment, and JET experiment. Also shown are an expected a particle parameter domain in ITER. Open circle shows a parameter domain of fast ions in discharge of E39672 of JT-60U experiment using N-NB*

emission rate increases with the proportion to the amplitude of the mode almost and has reached about 40% [21].

In JT-60U experiments using N-NB, a significant decrease up to 10 % of total neutron emission was observed when ALEs occurred. These results suggested transport of energetic ions by bursting modes [29, 30]. In particular this study of fast ion transport by TAE in JT-60U is very important for the assessment of alpha-particle transport in ITER.

Although transport of fast ion by TAE was observed as mentioned above, it is not, however, clearly understood yet whether this transport is due to loss or redistribution of energetic ions, or both processes are important so far. Because measured neutron value has been only volume-integrated value and it was not possible to investigate the detailed transportation of the fast ion.

In this study, in order to investigate the fast ion transport by TAE in detail, neutron emission profile measurement was established in JT-60U [31] and this was applied to the TAE experiment using N-NB for the first time. Since beam-thermal neutrons are dominant in such experiments with N-NB in JT-60U, change of the neutron emission profile indicates movement of fast ions produced by N-NB. This makes the neutron emission profile measurement a useful for the study of transport of fast ions under the presence of bursting modes induced by N-NB.

A measurement of neutron emission profile is of great importance for the knowledge of the profile of fusion power and the source of alpha particles. It is one of main diagnostics in ITER (which is called "neutron camera") [32]. Therefore establishment of a measurement method of neutron profile is highly desirable.

In large tokamak devices like JET [33] and TFTR [34], multi-channel neutron diagnostics system is installed in order to measure neutron profiles. The change of neutron emission rare by giant sawteeth and fishbone instabilities was observed in JET [33] and TFTR [35], respectively.

In this development of neutron emission profile measurement, by using Monte Carlo Code for Neutron and Photon Transport (MCNP) [36], the effect of shielding and scattering of neutrons for vacuum vessel and neutron emission profile monitor was estimated. Also, as neutron detector, the Stilbene neutron detectors developed by TRINITI laboratory in Russia have been installed in the JT-60U multi-channel neutron emission profile monitor for the first time. This detector combines a Stilbene organic crystal scintillator with a neutron-gamma pulse shape discrimination circuit. For the Stilbene neutron detector the calibration using neutron and gamma sources and the performance test on Fusion Neutron Source (FNS) in JAERI Tokai [37] were conducted.

Then, neutron emission profile measurement could be performed in JT-60U experiment. In neutral beam heated plasma, the neutron profile measured by Stilbene neutron detector is in a reasonable agreement with the calculation result by the TOPICS code [38].

The neutron emission profile measurements were carried out in TAE experiment using N-NB in order to investigate transport of fast ion by bursting modes. The results of measurements of neutron emission profile suggested that large amplitude bursting modes in the range of TAE gap frequency cause the redistribution of fast ions for the first time. Furthermore in this thesis , the change of fast ion density profile was estimated from the change of neutron emission profile [39].

In this thesis, the results of the neutron emission profile measurement and their implication of fast ion transport due to bursting modes such as ALEs in the range of TAE frequency induced by N-NB in JT-60U are presented.

Following is the plan of this thesis paper. A basic theory about Tokamak device and JT-60U are provided in chapter 2. The results of the thesis work are described in chapters 3, 4. The development of neutron emission profile measurement and the measurement of neutron emission profile in DD experiments is described in chapter 3. In chapter 4, the neutron emission profile measurement in AE experiment using NNB was presented. Furthermore fast ion transport by bursting mode estimated from the result of the measurement of neutron emission profile was discussed. Finally, the conclusion of the study in this thesis is presented in chapter 5.

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