### Observation of Internal structure of energetic particle driven MHD modes in the Large Helical Device

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In the burning plasma the energetic alpha particles enhance MHD instabilities such as toroidal Alfvén eigenmodes and these modes affect the particle transport and the plasma confinement. The study of the energetic particle driven MHD mode is important as the preparation study of the future alpha particle transport. In the Large Helical Device three microwave reflectometer systems have been installed to measure the density fluctuation in the wide radial area with a high spatial resolution. These systems are used for knowing the internal structures of each MHD mode and these temporal behaviors. One of the results is the energetic particle mode driven by the injecting neutral beam is strongly localized at the plasma core region and it is agreement with the theoretical expectation.

Keywords: Alfvén eigenmode, MHD, Density Fluctuation, Microwave Reflectometer, Large Helical Device

#### **1. Introduction**

In the burning plasma energetic alpha particles enhance magneto hydrodynamics (MHD) modes such as toroidal Alfvén eigenmodes (TAEs). Also the study of the energetic particle transport is one of the important issues and it is found that the correlation between the temporal behavior of the instability and the lost particle is quite high. That is an MHD mode affects the alpha particle transport and changes plasma confinement. Therefore energetic particle driven MHD instability has been studying in several magnetic confinement devices Usually MHD phenomena are observed by [1-4]. magnetic probes and the excellent analytical technique is developed to know toroidal and poloidal mode number and travelling direction. Also theoretical analysis using three dimensional code has been developing [5]. For the comparison between the simulation code result and the experimental result, it is important to measure directly the internal radial distribution of these modes.

In Large Helical Device (LHD [6]) recently we have been applying three types of microwave reflectometer system for measuring the radial distribution of the fluctuation, because the microwave reflectometer has a potential of the localized measurement by using the cut-off effect in the plasma core region. The density perturbations  $\delta n$  associated with the displacement  $\xi$  of a shear Alfvén mode is described by [2],

$$\frac{\delta n}{n} = -\nabla \cdot \xi - \xi \cdot \frac{\nabla n}{n} \cong \left(\frac{-2\hat{R}}{R^2} + \frac{\hat{n}}{L_n}\right) \cdot \xi.$$
(1)

Here *n* is the plasma density,  $\hat{n}$  is the density unit vector normal to the magnetic surface, *R* is the major radius,  $\hat{R}$ is the unit vector along a major radius direction, and  $L_n$  is the density scale length. Therefore it was found that the reflectometer can measure the internal structure of MHD phenomena such as energetic particle mode and Alfvén eigenmodes.

At first we have applied a fixed frequency reflectometer system to measure the low frequency fluctuation such as an interchange mode, etc. One of the reasons is the limitation of the memory size of the data acquisition. Recently the real-time fast data acquisition system has been developed in LHD [7] and the sampling rate of up to 10 MSample/sec is available to use. It makes the high frequency fluctuation measurable during the whole plasma discharge. Also we make the frequency variable reflectometer systems, so called Hopping reflectometer. To measure the fluctuation profile in the wide range, a reflectometry needs a lot of frequency sources. If the plasma condition seems to be steady during the frequency changing period, the radial profile can be measured each sweep in one plasma discharge. In this paper we present these reflectometer systems and some experimental results.

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### 2. Frequency Fixed E-band Reflectometer System

*E*-band fixed frequency heterodyne reflectometer system is utilized for the fluctuation measurement [8]. Currently the system has three channels of fixed frequencies of 78, 72, and 65 GHz. Power combined three microwaves travel to/from the LHD through the corrugated waveguide for avoiding the transmission loss. The extraordinary polarization wave is used. The simplified super heterodyne detection technique is used



Fig.1 Time evolution of reflectometer signal and frequency spectrum (Left) and these of magnetic probe signal (right)



Fig.2 Time evolution of fluctuation power of reflectometer signal. Including each frequency component is higher than 200 kHz (top), higher than 50 kHz and less than 200 kHz (middle), and less than 50 kHz (bottom), respectively.

for the receiver system. In LHD the real-time data acquisition system has been able to be utilized and the sampling rate is up to 10 MSample/sec by using a compact PCI based digitizer. The system is very convenient to observe MHD phenomena such as energetic particle driven Alfvén eigenmodes. The example of the temporal behavior of the reflectometer signal of 78 GHz and magnetic probe signal and these frequency power spectra are shown in Fig. 1. In this plasma discharge some bursts are repeatedly and in this figure one of the bursts is presented. Coherent spectra of around 8 and 16 kHz are caused by low-n mode oscillation. In the range of 100~150 kHz there are a lot of coherent mode. These modes are identified the n=1(n: toroidal mode number) TAE mode by the magnetic probe analysis. Also on the reflectometer signal it is observed higher mode around 230 kHz. Just after t=1.82s MHD-burst is occurred and at the same time TAE mode frequency components are rapidly disappeared shown in Fig. 2. Then passing 0.02s this mode is started to revive. This sudden disappearance may be caused that the distribution of high energy particle is changed by a MHD-burst. In this experiment the birth source of energetic particle is generated by the neutral beam. During this phenomenon is occurred, the injection power of neutral beam is kept constant. Therefore the TAE mode is re-exited quickly and then it keeps to a next burst.

# 2. Frequency Hopping *Ka*-band Reflectometer System

To know the radial distribution of fluctuation there are two methods in a reflectometry. One is the multi-channel system, and another is the wide band frequency source system. For the latter system, source frequency sweeps step by step in the whole frequency



Fig.3 Schematic view of Frequency Hopping *Ka*-band Reflectometer system

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Fig.4 Frequency spectrum of interferometer mode CW Reflectometer

range. The step width is limited by the characteristic time of the measuring fluctuation frequency. Of course, during the frequency change, the plasma condition and the fluctuation level are assumed to be constant. The schematic of frequency hopping Ka-band reflectometer system is shown in Fig. 3. The system uses voltage controlled oscillator (VCO) as a source. The output frequency of this source is easily changed by the external controlled signal. The output wave is amplified and also this frequency is multiplied by two. The reflected wave is mixed with a local wave for the heterodyne detection and intermediate frequency (IF) signal is amplified and detected. Data acquisition system is the same as the previous *E*-band reflectometer system.

The experiment is carried out that the axial magnetic field strength is 1.0 T, the averaged electron density is under 0.5x10<sup>19</sup>m<sup>-3</sup>, and neutral beam is injected with constant. The source frequency is swept full range every 200 ms and the number of the frequency step is 20. Each time of the launching frequency is 10 ms and data sampling rate is 1  $\mu$ s, then the data point is 10,000 and the frequency resolution is 100 Hz. It is enough to observe the MHD phenomena such as TAE. Figure 4 shows the frequency spectrum of the previous frequency fixed 78 GHz reflectometer signal. In this plasma condition there is no corresponding cut-off layer of 78 GHz wave and then this system is operated as an interferometer mode. We can see several continuous coherent frequency components. Figure 5 shows the radial profile of the fluctuation strength of the frequency hopping reflectometer signal during t=4.0-4.8s (4 sweep periods). It can be obtained that the frequency component around 200 kHz is large near at  $\rho$ =0.8 and the other component around 150 kHz is localized in the plasma centre. Here the meaning of the data points which are located under  $\rho=0$  is that these frequency waves are not reflected from the plasma and they are



Fig.5 (a) Shear Alfvén spectra for n=1 and Radial profile of the fluctuation component of *Ka*-band Hopping reflectometer in the integrated frequency range that (b) 175-220 kHz and (c) 120-170 kHz

come back from the opposite wall. The calculated shear Alfvén spectra is shown in Fig.5(a). The frequency gap of around 200 kHz is located near at  $\rho$ =0.7. It is well agreement with the measured profile data. On the other hand, the coherent frequency mode of around 150 kHz is lower than the gap frequency and the temporal behavior is different with the 200 kHz frequency mode. It looks like the energetic particle mode (EPM). However, strictly speaking, this signal is not only the phase fluctuation of the reflected wave and it is not directly related to the density fluctuation. Therefore the direct

phase measurement of reflected wave is necessary for the strict analysis of fluctuation.

# 2. Frequency Hopping V-band Reflectometer System

For more accurate fluctuation measurement we have developed a new system shown in Fig.6. Some components are added to the previous Ka-band system. Especially the single side band (SSB) frequency modulation is utilized for the direct phase measurement. Also the synthesizer is used as a source as a low phase noise source. The signal to noise ratio is up to 50 dB in the test of the system noise.

An example of this hopping system's measurement is shown in Fig.7. In this time window the launching frequency is changed from 52 GHz to 63 GHz and the step size is 1GHz with 50 ms duration. Some Alfvén eigenmodes can be observed in the whole launching frequency range. Disappointingly in this discharge the fluctuation is not kept constant and it can not be got the structure of the fluctuation mode. We plan to add more improvement in this system and will get the internal information of Alfvén eigenmodes in near future.

#### **Summary**

To study the internal structure of Alfvén eigenmodes, some reflectometer systems are installed on LHD. Both TAE and EPM modes can be observed with high resolution. Using frequency hopping technique the internal structure can be obtained. For the strictly analysis the direct phase measurement system has been applied. We will add more improvement in the system and study the Alfvén eigenmodes physics.

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Fig.6 Schematic view of Frequency Hopping V-band Reflectometer system



Fig.7 Temporal behavior of the Frequency Hopping V-band Reflectometer signal and its frequency spectra