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Localization of NTMs and Alfvén Eigenmodes in ECE Measurements on ASDEX Upgrade

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Introduction

The experimental program of the ASDEX Upgrade (AUG) tokamak focuses in large part on developing capabilities and knowledge that will bring about successful operation of burning plasma experiments such as ITER. Two important branches of the program dealing with physics of the plasma core are: (1) the development of a system to locate and suppress neoclassical tearing modes (NTMs) in real time and (2) studies of fast particle physics phenomena, such as Alfvén eigenmodes (AEs), the understanding of which will be vital for ITER with its foreseen large population of 3.5 MeV alpha particles. It is important in both cases to spatially localize the modes in question, and this can be accomplished using the electron cyclotron emission (ECE) diagnostic on AUG. Specifically, a 60-channel super-heterodyne radiometer measures second harmonic, X-mode ECE along a nearly horizontal line of sight near the tokamak midplane. The measurements are analyzed to produce radial electron temperature (T_e) profiles, a standard diagnostic technique for tokamaks [1]. After a recent data acquisition upgrade [2], the present capabilities of the instrument include T_e spatial resolution of ~1 cm and a sampling rate of 1 MHz; this is sufficient to make useful measurements both of NTMs and AEs, as is described below.

Localization of NTMs

A system for the real time stabilization of NTMs through the use of targeted injection of electron cyclotron resonance heating (ECRH) or current drive (ECCD) power is under development at AUG. NTMs can be destabilized by a seed magnetic island that perturbs the bootstrap current profile, an effect that becomes more likely with increasing plasma β—as such, they impose a limit on the achievable plasma pressure in a tokamak, and can cause substantial loss of confinement [3]. It is understood, therefore, that high performance experiments such as ITER will require a means of avoiding or actively suppressing NTMs in order to achieve desired values of β and prevent degradation of confinement including potentially damaging disruptions [4]. In the method discussed here, ECRH or ECCD power is deposited at the island location, which can restore the missing bootstrap current and stabilize the NTM. The role of the ECE diagnostic is to track the location of the NTM after it forms so that the ECRH/ECCD beams may be continuously steered to it. The details of this feedback control loop are shown in Figure 1.

As the NTM rotates with the plasma through the ECE line of sight, T_e at the magnetic island location fluctuates with the island rotation frequency. Crucially for this approach, these fluctuations are 180 degrees out of phase on opposite edges of the island, since the T_e flattening in the island causes the inboard side of the island to become cooler while the outboard side becomes hotter. Finding this phase transition locates the NTM in ECE "channel space". To narrow the analysis to the mode frequency itself and thereby strengthen the detection, the ECE signals are correlated against a reference signal from magnetic measurements; this reference corresponds to the toroidal mode number n of the particular NTM being sought (e.g. n = 2 for the 3/2 NTM in the standard scenario of this project). The key feature of the resulting profile of correlation amplitude vs. radiometer channel number is a zero-crossing corresponding to the center of the NTM. This zero-crossing is an unambiguous signature of the 180 degrees phase difference in T_e fluctuations, and is thus amenable to straightforward detection in real time. The result leads to spatial coordinates to be used for the ECRH/ECCD targeting. The amplitude of the magnetic reference signal reflects the amplitude of the NTM, and is therefore also used as a measure of the effectiveness of the NTM suppression.

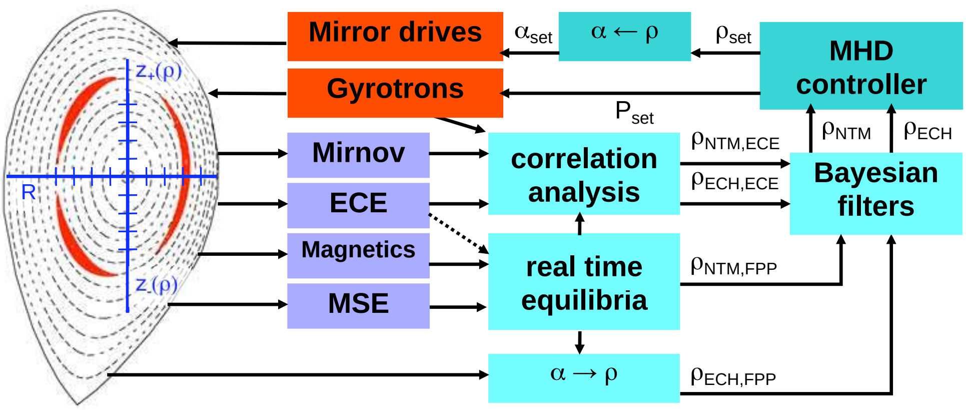

Figure 1. The real time NTM control loop. The NTM position is determined by the ECE-Mirnov correlation result mapped onto a real time equilibrium for flux coordinate ρ output. ECRH/ECCD mirror angles are updated, and modulated power deposition is located in ECE.

An example of the technique is shown in Figure 2, constructed from data taken during a discharge with a stationary 3/2 NTM. The ECE and magnetic reference signals for this discharge were all acquired in the same hardware environment, on the same local computer, as will be necessary for real time operation. The correlation profile construction and analysis algorithm locks on to the NTM position and demonstrates stable tracking for a time of approximately 1 second, which is long compared to the typical AUG NTM growth time of 100 ms. This 1 second tracking period represents approximately 100 cycles of the real time measurement and calculation loop (target cycle time = 10 ms). It is found for this discharge and other similar cases that at least 1 ms of sampling, corresponding to ~20 mode periods, is required for reliable NTM position tracking. The position result typically shows no further improvement for sampling periods greater than 5 ms. These constraints are compatible with the 10 ms real time target cycle. The analyses were performed using offline data, but employing the same algorithms to be implemented in real time.

For each real time cycle, the ECE channel number associated with the NTM center is analyzed with results from a real time magnetic equilibrium solver to yield the magnetic flux coordinate ρ of the NTM. Real time motional Stark effect (MSE) data are used to improve the accuracy of the equilibrium in the plasma core. A real time version of the beam tracing code TORBEAM calculates the necessary adjustments to the angles of the steerable ECRH/ECCD mirrors such that deposition of the beams at the magnetic flux surface of the NTM is maintained. To verify the achieved deposition location of the ECRH/ECCD, the beam power may be modulated. The modulation signature may be observed in the ECE profile and may be compared to the NTM location. Initial experiments have shown a clear modulation signature, for example, for 98% duty cycle ECRH (49 ms on, 1 ms off); the successful detection of this order of "off" time is a promising result for the NTM control application.

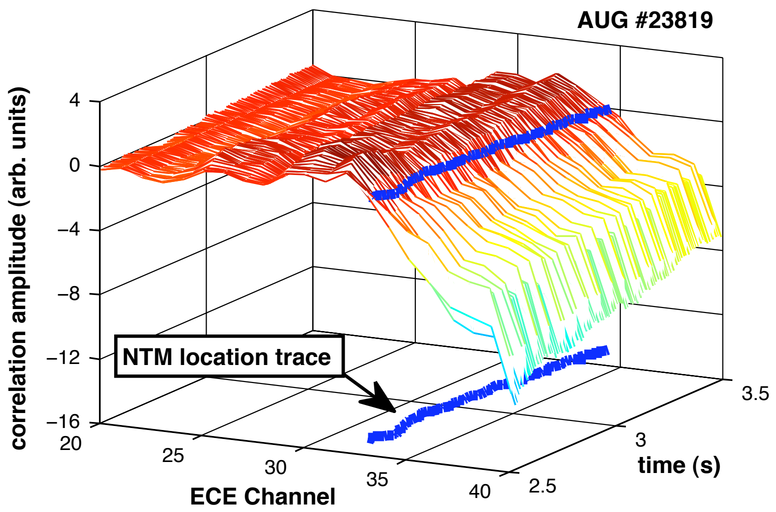

Figure 2. Tracking a 3/2 NTM via correlation of ECE and magnetic reference signals. A time series of correlation profiles is shown. Each profile is constructed by correlating all relevant radiometer channels with the single magnetic reference. The zero-crossing of each profile indicates the NTM center. The blue trace of zero-crossings is projected onto the ECE channel-time plane to illustrate the algorithm output.

The real time diagnostic environment at AUG is being expanded using "Hotlink II" and "SIO" hardware [5] as a data acquisition standard. In the case of the ECE diagnostic, 30 of the 60 radiometer channels have now been migrated to this setup for testing and comparison with the old (Hotlink I) system. The new standard offers greater data reliability and throughput, as well as bidirectional programming I/O via fiber optic link. The latter makes the instrument significantly more versatile by allowing, for example, uploading of individual gain settings to the radiometer channel amplifiers optimized for specific experiments. Based on this hardware standard, real time software libraries for data acquisition and analysis have been developed that facilitate the real time data flow needs of the NTM control project. Throughout the remainder of the present experimental campaign, this data environment will be benchmarked and commissioned, culminating in closed loop operation.

Localization of Alfvén Eigenmodes

Alfvén eigenmodes are fast ion-driven MHD fluctuations [6] that, in a fusion reactor such as ITER, may trigger excessive alpha particle losses. Understanding and limiting this process will be necessary for the successful operation of such experiments [7] since, to draw a parallel with NTMs, the detrimental effects of fast alpha particle expulsion could range from undesirable degradation of fusion performance to serious damage to the machine. In AUG, a study of AEs is underway using a combination of diagnostics: direct measurements of particle expulsion via a fast ion loss detector (FILD), boundary measurements of magnetic perturbations from Mirnov coils, and core measurements of ECE and soft x-rays. For example, toroidal Alfvén eigenmodes (TAEs) may occur in AUG with frequency range 100-200 kHz, and they can create T_e fluctuations measurable by the ECE radiometer. Figure 3 shows ECE and FILD measurements from a discharge in which several TAEs with various mode numbers occur. It is possible to isolate the T_e behavior of a specific mode or modes in particular ECE channels, thereby providing spatial information on the origin of the fast ion losses measured in FILD. In addition, reverse shear Alfvén eigenmodes and Alfvén cascades have also now been observed in the ECE data, and because of the inherent capability of localizing these modes in space it is possible to study, for example, the spatial overlap of the various kind of AEs and the resulting effect on fast ion losses [8]. An effort to expand the coordinated analysis of complementary AE diagnostics on AUG is ongoing as part of the overall AE study.

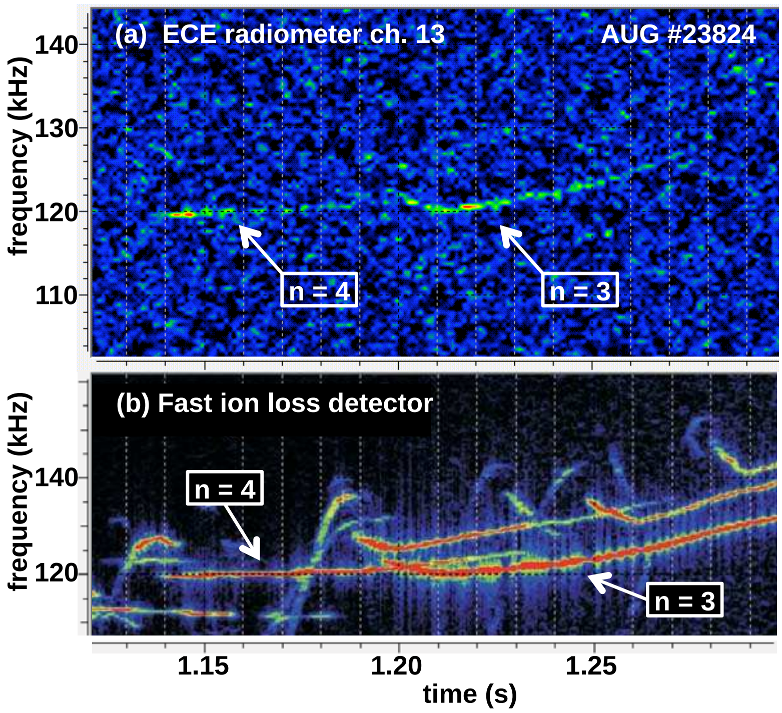

Figure 3. ECE and FILD data from a discharge with several TAEs, illustrating the possibility of spatially localizing particular modes. (a) A spectrogram of the ECE radiometer channel in which the peak amplitudes for two of the TAEs (*n* = 3 and *n* = 4) were detected. (b) The FILD spectrogram for the same time period, showing the fast ion losses from TAEs of many mode numbers—the two that were isolated in ECE are indicated.

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