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Measurement of NTMs, Modulated ECRH Deposition, and Current Ramp-Up MHD Activity Using the Upgraded 1 MHz ECE Radiometer on ASDEX Upgrade

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Introduction

The ASDEX Upgrade tokamak (AUG) employs a 60-channel super-heterodyne radiometer for the measurement of second harmonic, X-mode ECE along a horizontal line of sight near the tokamak midplane. The measurements lead to radial electron temperature (T_e) profiles, following a well-established technique [1]. The front end of the radiometer, including the lens, polarizing grid, and waveguide antennas has been described in [2]. The microwave receivers and down-converters, power splitters, band-pass filters, Schottky diode detectors, and video pre-amplifiers conform to the standard approach described in [1]; the performance of these sub-systems and the properties of given plasma discharges lead to T_e spatial resolution of 1-2 cm. A new data acquisition (DAQ) sub-system with sampling rate 1 MHz has recently been added to the system. The original DAQ with sampling rate 31.25 kHz has been retained, in parallel, for validation. Details of this upgrade and initial plasma measurements comparing the old and new DAQ have been presented in [3]. Briefly, the upgrade features new amplifiers for each radiometer channel, each with 2 MHz bandwidth and software programmable gain (from 1-100); the latter allows the sensitivity profile of the radiometer to be optimized for each plasma discharge. The fast DAQ allows measurements of plasma phenomena on the MHD timescale, such as neoclassical tearing modes (NTMs), and the role of ECE in a real-time control loop on AUG for the suppression of NTMs via targeted deposition of electron cyclotron resonance heating (ECRH) is described here. Also, in a related ECE technique, MHD activity during the current ramp-up phase of certain AUG discharges is being studied in an effort to constrain *q*-profiles by locating modes on rational surfaces.

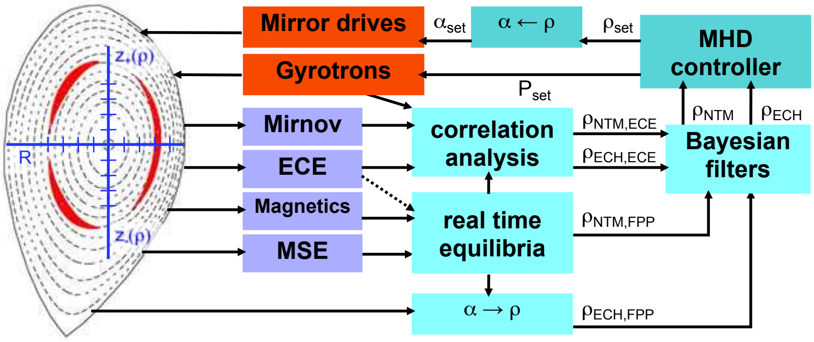

Fig. 1. Real-time NTM control loop. NTM and ECRH deposition locations are determined via ECE and real-time equilibria. ECRH mirror angles are continuously updated to maintain deposition at NTM location.

NTM Control

NTMs limit the performance of high-β tokamaks, and active stabilization of these modes is envisioned to be necessary for operation of devices such as ITER [4]. The real time NTM suppression system being implemented on AUG is depicted in Figure 1 (and is described in greater detail in [3]). The approach relies in part on locating the NTM via ECE measurements, and, since (3,2) NTMs in AUG commonly occur with rotation frequencies greater than 20 kHz, the upgraded fast ECE DAQ is required for this task. Figure 2 shows some of the first measurements of an NTM discharge in AUG using the upgraded system. T_e measured by ECE at the NTM island location fluctuates with the island rotation frequency, oscillating between a flattened and unflattened T_e profile as the island repeatedly passes in and out of the ECE line of sight. The maximum fluctuations occur at the widest part of the island separatrix (radially inside and outside with respect to the "O-point"), and the relative phase of these maxima is π, since the T_e flattening in the island causes the hot side of the island to become cooler while the cool side becomes hotter. This phase difference is a feature that may be exploited to locate the NTM. The NTM is also measured using the Mirnov coil diagnostic on AUG. NTMs of specific poloidal and toroidal mode numbers can be detected by constructing superpositions of Mirnov signals that correspond to those mode numbers. The correlation of the mode-specific signal with each ECE channel signal may be calculated and a correlation profile constructed [5]. The profile extrema are found at the ECE channels closest to the hot and cold sides of the O-point separatrix, and are in phase and out of phase, respectively, with the oscillation in the mode-specific Mirnov signal. The zero-crossing of the profile between these extrema corresponds to the center of the island. This algorithm is currently being implemented with the upgraded ECE DAQ, and it has also been tested with recent AUG discharges using the original DAQ [3]. As illustrated in Figure 1, the

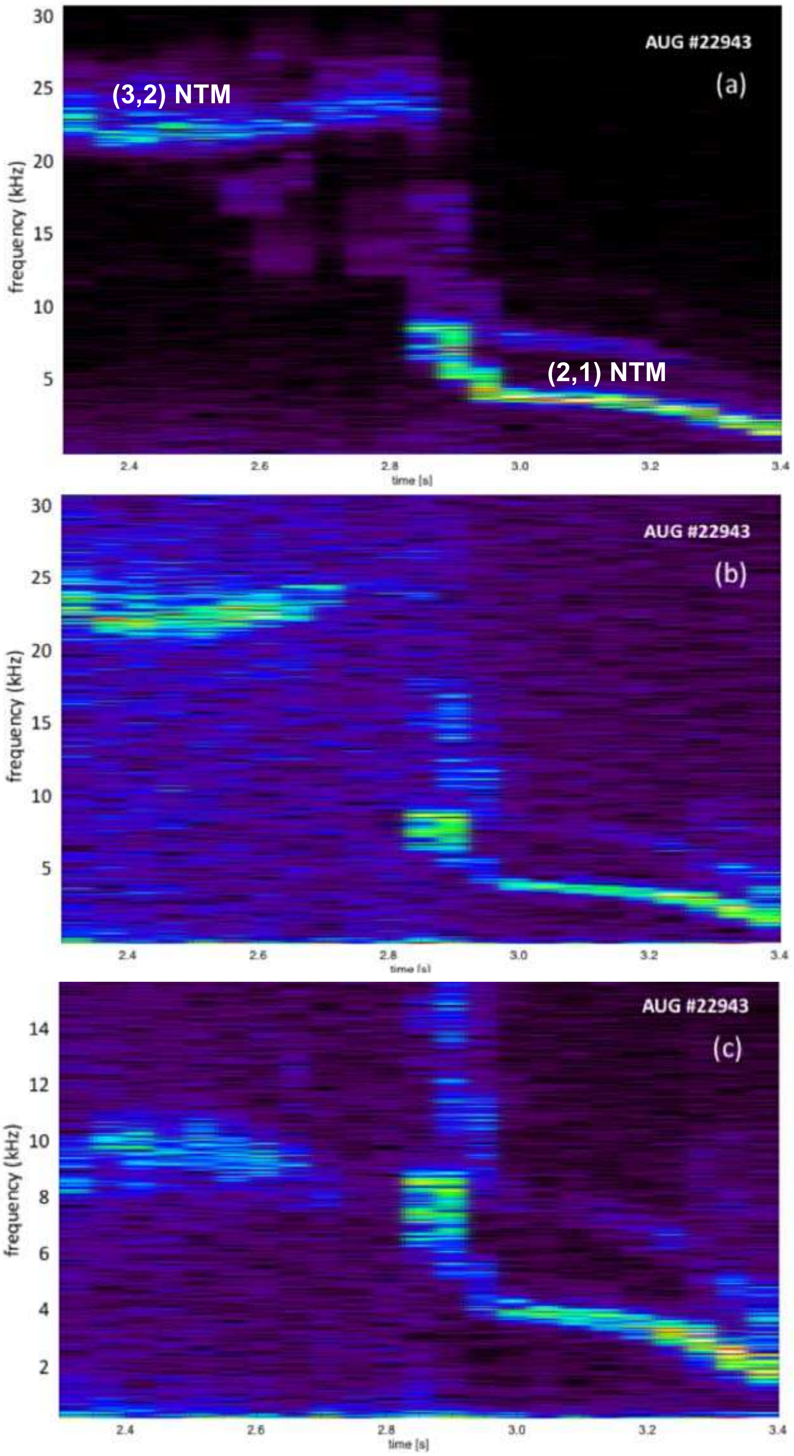

Fig. 2. AUG discharge exhibiting (3,2) NTM from 2.3-2.9 s, ~22 kHz, and (2,1) NTM from 2.9-3.4 s, ~4 kHz, as shown in (a), a spectrogram of a representative Mirnov coil signal. (b) Spectrogram of an ECE radiometer channel using the upgraded DAQ; both NTMs are temporally resolved, matching the frequency signature in (a). (c) The same radiometer channel using the original DAQ; the frequency profile of the (2,1) NTM is accurately reproduced, but only an aliasing artifact ($f_{artifact} = f_{DAQ} - f_{mode}$) is visible for the (3,2) NTM.

ECE channel values characterizing the boundaries and center of the NTM are associated with flux surface coordinates using real time equilibrium reconstruction calculated via function parameterization and incorporating real time motional Stark effect (MSE) measurements. The ECRH steerable mirrors are pointed such that ECRH power will be deposited at the flux surface corresponding to the center of the island. The real time equilibria are also used to calculate the location of the rational q-surface where the NTM will form. Prior to NTM formation, the ECRH mirrors may be steered to point at this surface. A combination of the ECE-based NTM location and equilibrium-based q-surface location is processed by a Bayesian filter [6] to optimize the targeting of the ECRH.

The ECRH deposition location can be observed via ECE by modulating the injected power. T_e fluctuations appear at the flux surfaces being heated, with maxima in amplitude and phase occurring at the ECE channel located closest to the flux surface on which the ECRH deposition is centered. For the NTM control loop, the modulation frequency must be high enough to effect control faster than the typical AUG NTM growth time of 100 ms, but must be low enough to allow for measurable response in T_e. This compromise will be investigated during the development of the NTM control system. An initial experiment in this vein, a high heating power NTM discharge, is shown in Figure 3. Here, off-axis ECRH is deposited on the high field side, and the resulting modulated T_e is measured by the ECE radiometer at corresponding flux surfaces on the low field side. A peak in T_e oscillation amplitude at the 30 Hz modulation frequency is readily apparent; however, at this low frequency, the phase peak expected at the same location was difficult to discern. For the NTM control loop, the peak ECE channel is associated with a flux surface via real time equilibrium reconstruction. An additional estimate of the ECRH deposition flux surface is produced by a TORBEAM simulation look-up table for a correspondence between mirror angle and flux surface.

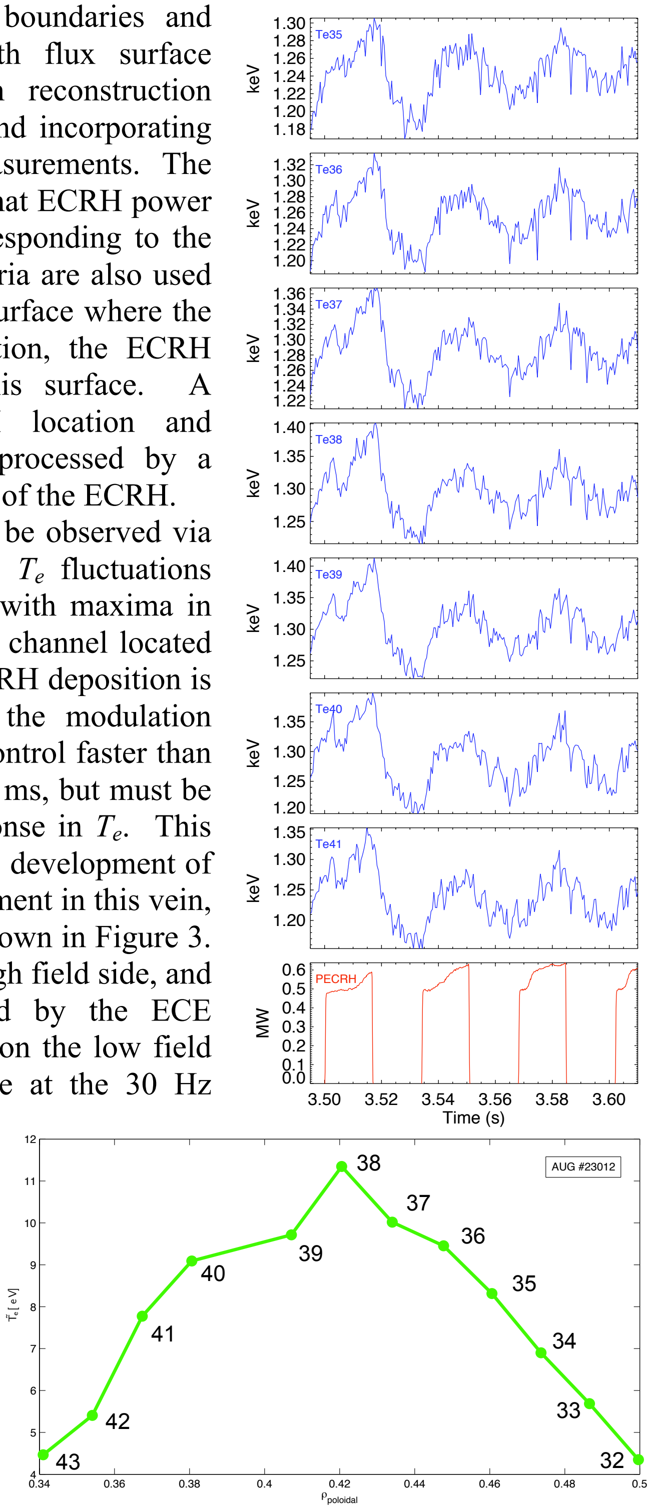

Fig. 3. AUG #23012: 140 GHz ECRH with modulation at 30 Hz, 50% duty cycle. ECE radiometer T_e fluctuation at 30 Hz shows a clear peak at ch. 38 (lower plot; reflects one modulation cycle, t = 3.500 – 3.536). Time traces for chs. 35-41 (upper plots) show local T_e response over three modulation cycles.

ECE Measurements of MHD Activity during Current Ramp

The evolution of the q-profile during the current ramp-up phase of a tokamak discharge is of interest in understanding how to produce certain discharge scenarios, such as the improved H-mode on AUG. Any experimental knowledge of the locations of rational q-surfaces in the plasma during ramp-up is valuable in constraining the equilibrium and q-profile reconstruction of a discharge, and for use as an input in transport modelling of the relevant scenario. One such method of locating rational surfaces is to look for MHD activity of known toroidal and/or poloidal mode numbers in the radial T_e profile of ECE measurements, thereby locating the mode radially. The mode numbers may be determined by examining magnetic measurements from toroidal and poloidal arrays of coils, and these measurements also provide the mode frequency to look for in the ECE data. As an example of this technique, we take the improved H-mode discharge AUG #20995. Figure 4a shows the onset of a low frequency mode (~200 Hz), as measured by seven adjacent ECE radiometer channels. A phase difference of π is apparent between the outer three and inner three channels, indicating this mode is likely a magnetic island centered on the center ECE channel. A contour plot of T_e (Figure 4b) confirms the island signature, and also the location of its center. Magnetic measurements from this discharge confirm the mode frequency and indicate a toroidal mode number n = 1. It is likely that the poloidal mode number m = 1 as well, since the ECE channel associated with the island center is seen to be near the q = 1 surface (Figure 4c). This ECE-based calculation thus constrains the radial location of q = 1 at this time in the current ramp. It is envisioned to use the upgraded ECE DAQ on AUG to make this kind of calculated rational q-surface location available in real-time.

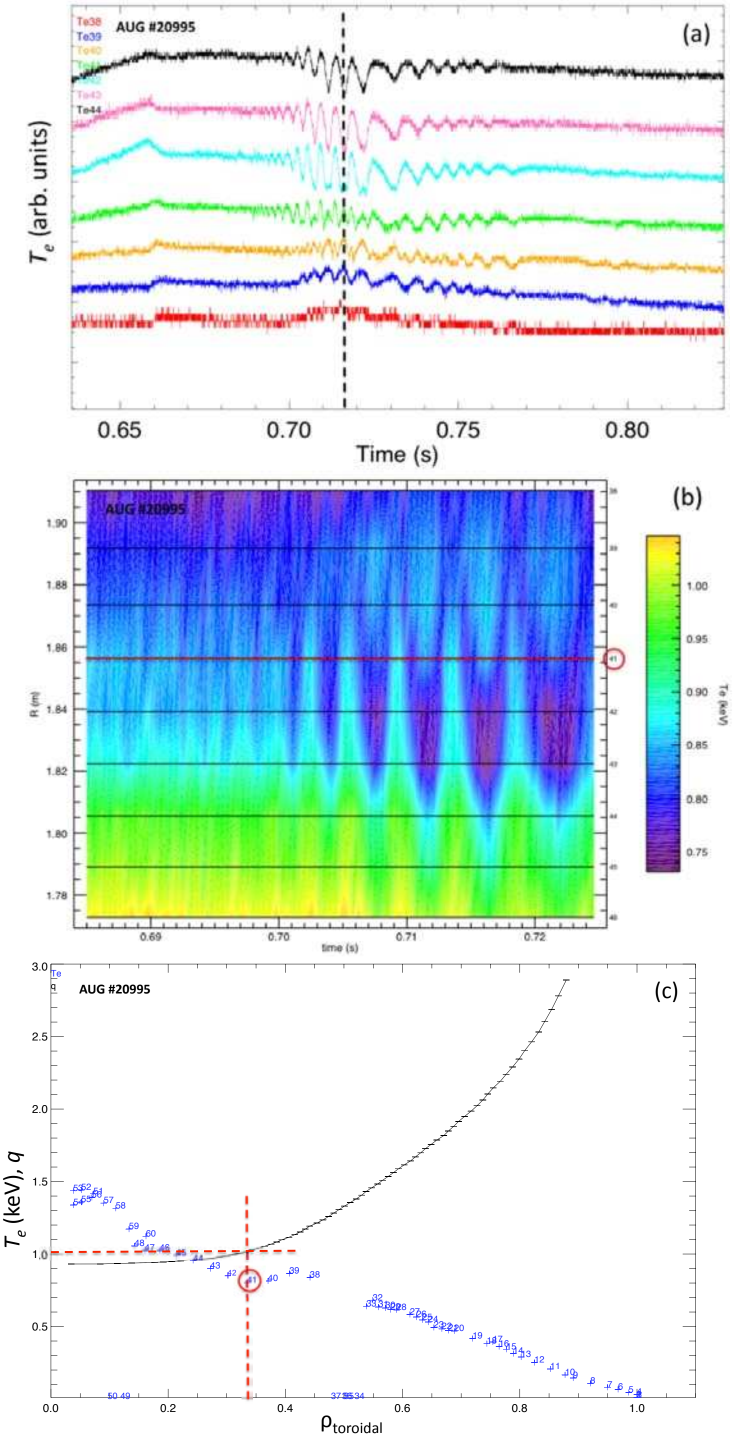

Fig. 4. Magnetic island observed in ECE during current ramp of AUG #20995. (a) ECE radiometer T_e time traces (dashed line illustrates phase difference). (b) T_e contour map. (c) Radial T_e and q profiles (mode location in red).

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