

ECE-Imaging measurements of the 2D mode structure of Reversed Shear Alfvén Eigenmodes at ASDEX Upgrade

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Introduction

2D electron temperature measurements of the mode structure of Reversed Shear Alfvén Eigenmodes (RSAEs) were performed on ASDEX Upgrade, using the recently installed Electron Cyclotron Emission Imaging diagnostic [1,2]. RSAEs are a type of Alfvén instability, destabilized when an off axis minimum in the q -profile, q_{min} , exists, and a sufficient drive from resonant fast ions is present (see [3] and references therein for a review on Alfvén instabilities). As these modes (and other types of Alfvén instabilities) can cause significant transport or loss of fast ions (and fusion reaction products in future reactors), an accurate experimental determination of their properties is needed.

ECE-Imaging Diagnostic and Data Filtering

The recently installed ECE-Imaging diagnostic on ASDEX Upgrade [1,2] provides a localized, high resolution 2D measurement of the electron temperature and its dynamics. The principle of a 2D ECE-Imaging diagnostic is comparable to a standard 1D heterodyne ECE radiometer, except that multiple lines of sight (16 on AUG) are simultaneously quasi-optically imaged onto a linear array of (16) Schottky diode detectors (see figure 1). Each of the lines of sight is treated as a 1D ECE radiometer, measuring the ECE intensity in a number of frequency bands (8 on AUG). This results in a direct 2D measurement of the electron temperature in a 2D array of 8 (horizontal) by 16 (vertical) positions (128 channels total) in the poloidal plane, covering an area of typically 13 by 40 cm. The position of this measurement area can be adjusted, both by tuning the diagnostic to different frequencies and by shifting the position of the focal plane. For these experiments, the system was tuned to measure close to the radius of the minimum in the q -profile (range $R=1.80$ - 1.90 m), and the system was set to full time resolution (Video bandwidth 400kHz, sampling rate 1 MHz). The spatial resolution of the system is comparable to the inter-channel spacing in all directions.

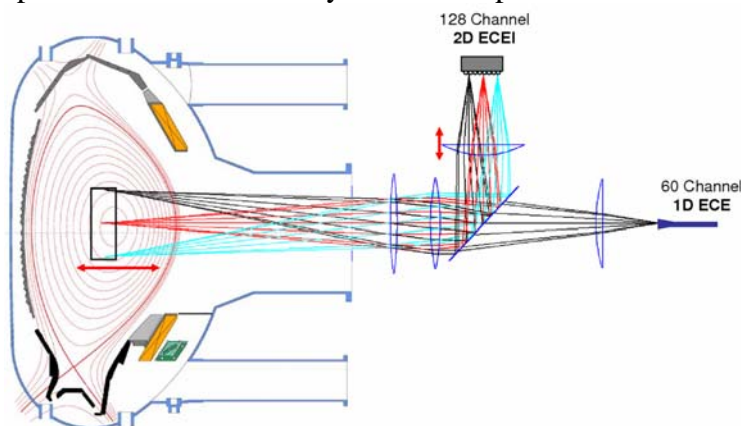


Fig. 1: Overview of the ASDEX Upgrade ECE-Imaging system. The 16 lines of sight are imaged onto a 16 element 1D array of detectors. The electron temperature is measured at 8 positions along each line of sight, giving 128 channels in an 8 by 16 array in the poloidal plane. The position of the focal plane can be shifted by translating one of the lenses. Part of the ECE-Imaging optics is shared with a 60 channel 1D ECE radiometer.

The accuracy of any ECE diagnostic is limited by thermal noise, which in these experiments amounts to a relative noise level of about 3%. The relative temperature fluctuations associated

with RSAEs are about 1%, so significantly below the noise level. To overcome this noise, the data has been filtered by both singular value decomposition (SVD) filtering and Fourier frequency filtering. The SVD filtering (described in detail in [2]) enhances the coherent data content (fluctuations present on most channels simultaneously) and filters out most of the (incoherent) noise. After filtering, direct observation of small amplitude fluctuations like the RSAEs is possible.

Frequency, Amplitude and Mode number of RSAEs

In figure 2a a spectrogram of the current ramp up phase of ASDEX Upgrade shot 25528 is given, showing a multitude of RSAEs, most of which show the typical fast increase in frequency as the discharge evolves. This spectrogram is the averaged amplitude spectrogram over all 128 ECE-Imaging channels, and shows averaged mode amplitudes up to 0.5%. The peak amplitudes are about three times higher, see next section. As the q -profile evolves, with q_{min} slowly decreasing and crossing rational values, modes with different mode numbers m/n become resonant and are destabilised. The wave vector k_{\perp} (perpendicular to the magnetic field) for an RSAE with poloidal and toroidal mode numbers m and n , that was triggered when q_{min} crossed the rational value m/n , is given by [3]:

$$k_{\perp} = |m/q_{min} - n|/R \quad (1)$$

The dispersion relation for transverse Alfvén waves like RSAEs is $\omega = k_{\perp} v_A$ ($v_A \propto B/\sqrt{n_e}$ is the Alfvén frequency), so the RSAE frequency is very sensitive to the value of q_{min} , rapidly increasing as q_{min} drops. A spectrum like figure 2a can be used to determine the evolution of q_{min} , from the characteristic succession of the various RSAEs. Low order rational q_{min} crossings, where multiple RSAEs are triggered simultaneously are easiest to recognize. In figure 2a, three such crossings at $q_{min}=3$, 2.5 and 2 are indicated.

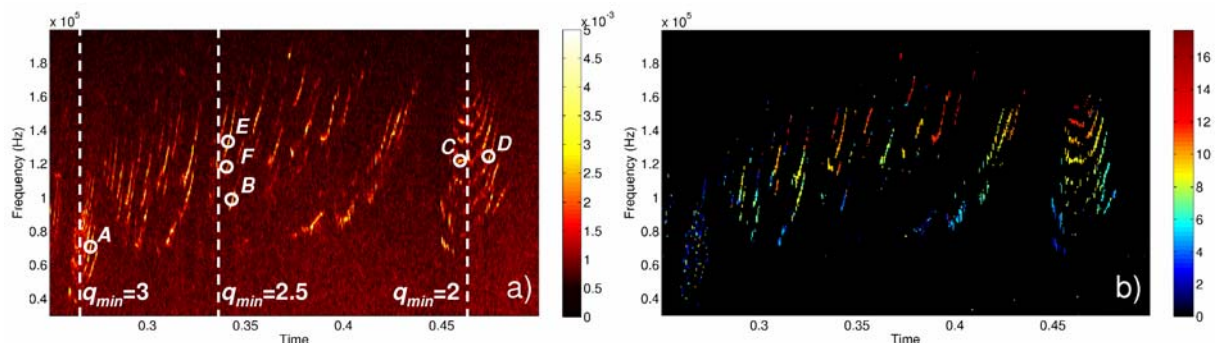


Fig. 2: A large variety of RSAEs is observed by ECE-Imaging (in AUG shot 25528) as q_{min} gradually drops during the evolution of the discharge. Figure a) gives the amplitude spectrogram, averaged over all ECE-Imaging channels, indicating some of the major q_{min} crossings. An estimation of the poloidal mode number m for these modes is given in b).

The spectrogram in Figure 2b gives an estimation of the poloidal mode number m for the various RSAEs. Only modes above a certain average amplitude threshold (0.15%) are shown. This estimation has been derived from the phase relations between five selected ECE-Imaging channels approximately at the radius of q_{min} (channels 8/2, 9/2, 10/2, 11/2 and 12/2, where the first number is the line of sight counting from the top, and the second number the radial channel number counting from the high field side). The gradient of the phase versus channel spacing is a measure for m . The known mode number $m=10$ of mode E (see section on NOVA simulations) has been used to calibrate the spectrogram. As expected, a large variety in m , ranging from about 4 to 15, is observed. The toroidal mode number n is not measured by ECE-Imaging, but can be inferred from the known value of q_{min} .

2D Mode Structure of RSAEs

In figure 3, the amplitude and mode structure for four selected RSAEs is shown. These modes, indicated in figure 2a, are referred to as modes *A* to *D*. The figures represent a 2D map of the Fourier components of a selected point in the Fourier spectrogram, and hence represent the harmonic content of a selected frequency band at a selected time interval (both set by nfft, here chosen to be 1024, and the sampling rate of 1MHz). The mode amplitude plots show the absolute Fourier amplitude, and the mode structure plots show the real part of the complex Fourier component.

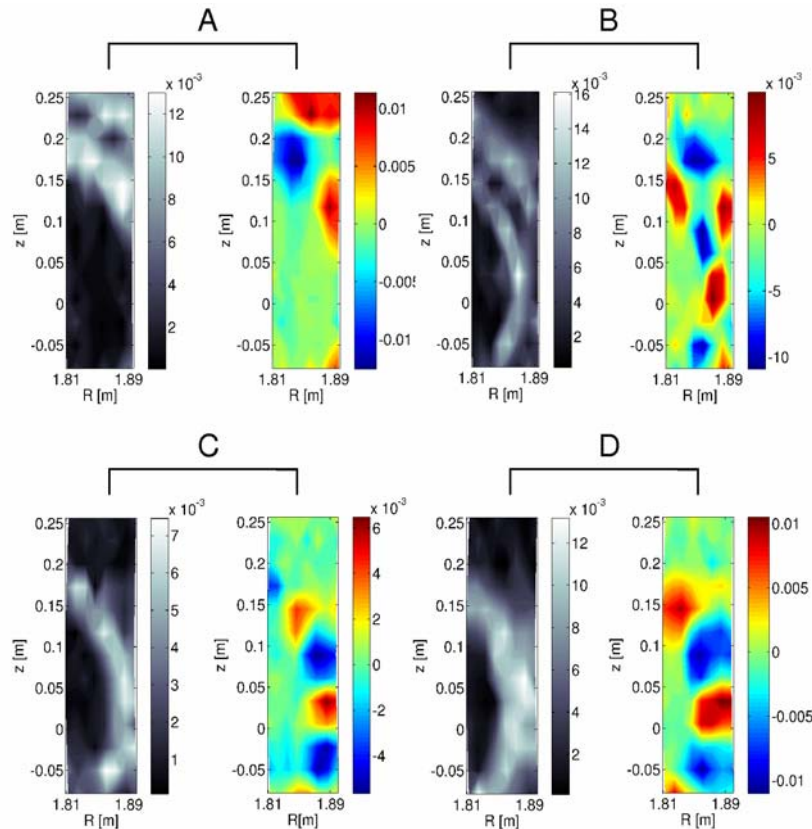


Fig. 3: Amplitude and mode structure for selected RSAEs. These modes (A-D) are also indicated in figure 2a). The figures show modes with a variety of mode numbers, localisation (minor radius), radial width and radial mode structure (A and B have a second radial harmonic).

The figures show temperature fluctuations with a variety of poloidal mode numbers, which are highly localized in minor radius (around the radius of q_{min}). The typical peak relative amplitude of the modes is around 1 to 1.5%. The minor radius of the modes is seen to decrease with time; mode *A* at 0.27s is clearly located at a larger minor radius than mode *D* at 0.47s, which is explained by the expected inward evolution of the radius of q_{min} . The radial width of the modes also varies significantly, for instance mode *C* is much narrower than mode *D* (see also [4]). The most striking difference between the modes is however their radial mode structure. Modes *C* and *D* show a single amplitude maximum in radius (the mode forms a single ring in the poloidal plane), whereas modes *A* and *B* have two maxima in radius (two rings). The oscillations on these two rings are in counter phase. These higher radial harmonic modes, previously observed by 1D measurements [5], are seen to have a slightly lower frequency than the simultaneously existing fundamental harmonic mode with the same mode numbers.

These ECE-Imaging data are the first local 2D temperature measurements of RSAEs, and represent a valuable extension to previous 1D temperature measurements [5,6].

First Comparison to Nova Simulations

A preliminary comparison of the observed mode structures with simulations using the NOVA code [7] has been performed. Two modes, modes *E* and *F* as indicated in figure 2a, both with the same mode numbers ($m=10$ and $n=4$ that appeared just after the $q_{min}=2.5$ crossing) have been chosen for the simulation. The difference between these two modes lies in the different radial structure. Mode *E* is the fundamental radial harmonic, mode *F* the first radial harmonic. The main inputs for NOVA, taken from experiment, are the MHD equilibrium and the profiles of temperature and density. As shown in figure 4, the experimental and simulated mode structures match well for both modes. The poloidal mode number m seems the same, indicating the experimental modes were identified correctly as the $m/n=10/4$ modes. It should however be noted that the outcome of the NOVA code is very sensitive to the exact shape of the q -profile. The exact position of the minimum in q is not (accurately) measured experimentally, and has been chosen such that the NOVA output resembles the ECE-Imaging data best. Hence, the value of the ECE-Imaging data lies just as well in providing input for codes such as NOVA as in verifying them.

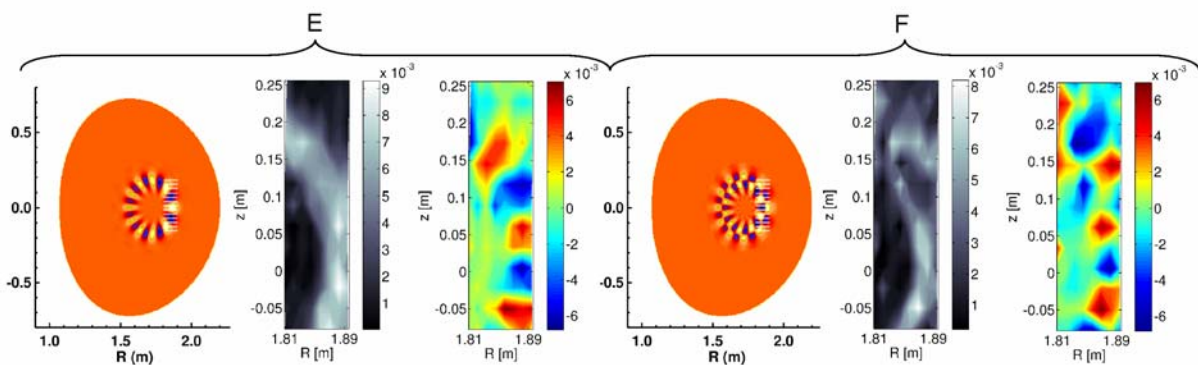


Fig. 4: Comparison between the ECE-Imaging measurements of two selected modes (E and F, as indicated in figure 2a) with the NOVA code. Both modes have the same mode numbers ($m=10$, $n=4$), but different radial harmonics.

Conclusion and Outlook

The measurements presented in this paper show that ECE-Imaging is capable of imaging the 2D structure of RSAEs with good spatial and temporal resolution and an accuracy far better than the thermal noise level. This data gives information on the frequency, amplitude and spatial mode structure of RSAEs, simultaneously providing an accurate measurement of the value and position of the local minimum in q . A preliminary comparison has been made to the theoretical NOVA code, but in future a more detailed comparison to NOVA and other codes will be undertaken. Also, measurements of a broader range of Alfvén instabilities (like toroidal Alfvén Eigenmodes TAEs) is planned, hopefully contributing to a better understanding of the fast ion transport associated with these instabilities.

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