Stochastic heating of thermal ions by compressional Alfvén eigenmodes in NSTX

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In neutral beam heated discharges in NSTX, the observed ion temperature is sometimes higher than what could be expected from the balance between collisional heating due to the fast ions and losses caused by transport and collisions with electrons. At the moment when the beams are switched on, the ion temperature can also rise to these high levels on time scales shorter than the slowing-down time of the fast ions, which implies that there exists a source of heating in excess of the collisional beam ion heating. It has been proposed [1] that this heating originates from interaction with compressional Alfvén eigenmodes (CAEs) [2], which are commonly observed in beam heated discharges. The proposed mechanism consists of two steps; first the energy is transferred from the fast ions to the waves by resonance, and then from the waves to the thermal ions by stochastic heating. The latter is a non-resonant process, which is possible in these discharges because several Alfvén eigenmodes occur simultaneously at around half the ion cyclotron frequency when the beams are turned on [3].

In the present study, we model the process quantitatively, by following thermal ions in the CAE eigenmodes calculated with the eigenmode code CAE3B [4]. A large number of ions are tracked in the full gyro-orbit code Gyroxy [5] under influence of the eigenmodes, and the evolution of the kinetic energy is monitored. Presently, the eigenmode amplitude is treated as a free input parameter, but we are planning to determine the experimental CAE amplitudes from density fluctuation measurements with the high-k diagnostic. It will then be possible to assess if the proposed heating mechanism can supply the excess heating inferred from transport modelling.

Eigenmodes

The eigenfrequencies and two-dimensional structure of the eigenmodes are calculated with the CAE3B code [4] which solves the linearised cold plasma equations for the three perturbed magnetic field components. It includes the Hall term and terms related to the equilibrium current. For numerical reasons, the shear Alfvén branch is excluded by assuming that the operator $v_A^2/(\omega^2 B^2)(\mathbf{B}\cdot\nabla)^2$ is small when operating on the perpendicular components of the perturbed field $\delta\mathbf{B}$.

As an example, we take the NSTX equilibrium of discharge 130335 at $t = 0.48$ s. In the spec-

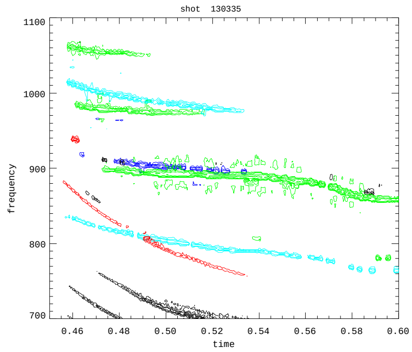

Figure 1: Magnetic spectrum for discharge 130335.

trum measured by magnetics pick-up coils, see fig. 1, the signals in green, blue and cyan are identified as counter-rotating CAEs with toroidal mode numbers $n = 3$, 4 and 5, respectively. A few examples of eigenmodes found with CAE3B for this equilibrium are shown in fig. 2. Identification of calculated eigenmodes with measured ones is in general difficult. The calculated eigenfrequencies are expected to differ from the measured ones because of the Doppler shift due to plasma rotation, and also because the calculation boundary in CAE3B is at the last closed flux surface, excluding the evanescent tail in the vacuum region from the eigenmode solution. The latter fact is likely to lead to an overestimation of the eigenfrequencies. However, since the stochastic heating process relies on the simultaneous existence of many modes, it is not so sensitive to the exact frequencies, as long as they are in the observed range, and the number of modes is correct.

Heating

The CAEs are loaded into the Gyroxy code [5], taking care to maintain $\nabla \cdot \mathbf{B} = 0$ to the required numerical accuracy, and not to introduce any spurious parallel electric field. The very small parallel electric field caused by electron inertia is determined separately and included in the particle simulations. Figure 3 shows simulations for one 200 eV ion in situations with different numbers of eigenmodes (each eigenmode has the amplitude $\max(\delta B)/B_{\rm axis} = 2 \cdot 10^{-3}$). Without collisions, the particle energy oscillates due to the eigenmodes, but on average remains constant. With both eigenmodes and collisions (only pitch-angle scattering) included, the behaviour becomes non-adiabatic, and the particle tends to gain energy.

The left plot in Figure 4 shows the time history of the mean energy for 8000 ions at mid-radius initially at 100 eV. To assess the overall heating, ions with a range of initial energies $(1 - 1000$ eV) and normalised radii $(r/a = 0.1 - 0.7)$ are simulated. The result is convoluted with a Maxwellian to give a mean particle heating. For particles with high initial energies, the

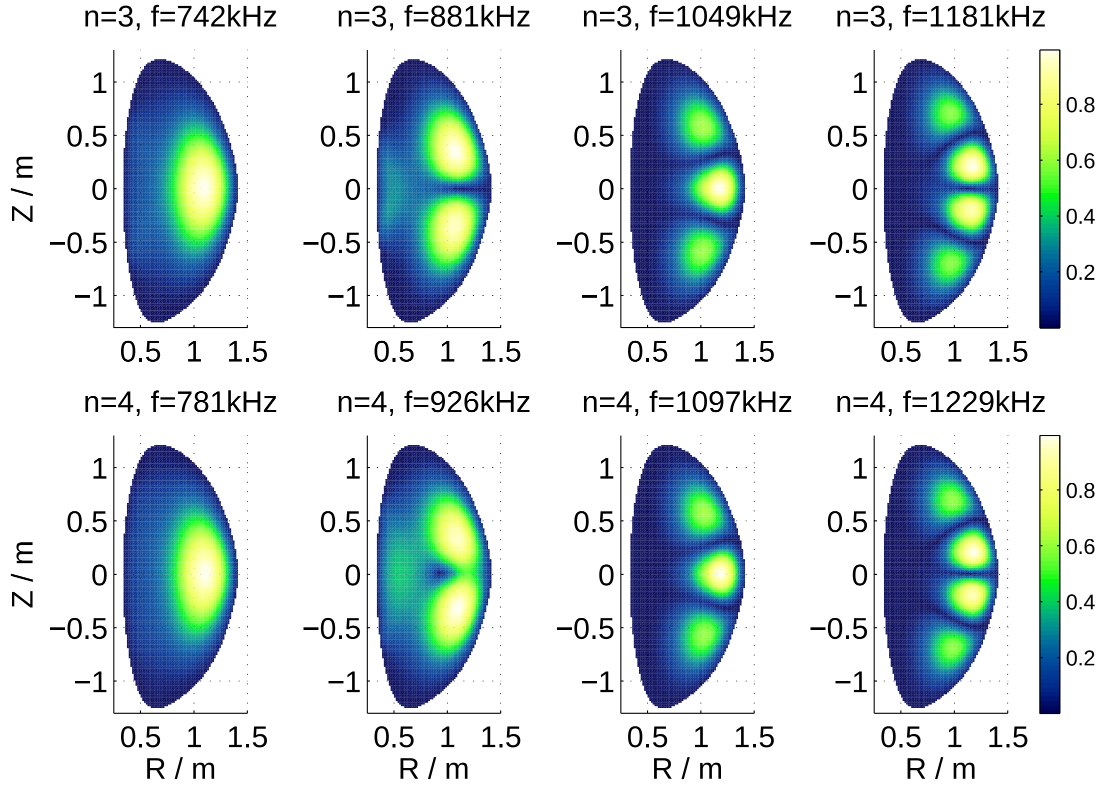

Figure 2: Envelope of the parallel component of the magnetic field perturbation for eigenmodes with $n = 3$ and $n = 4$.

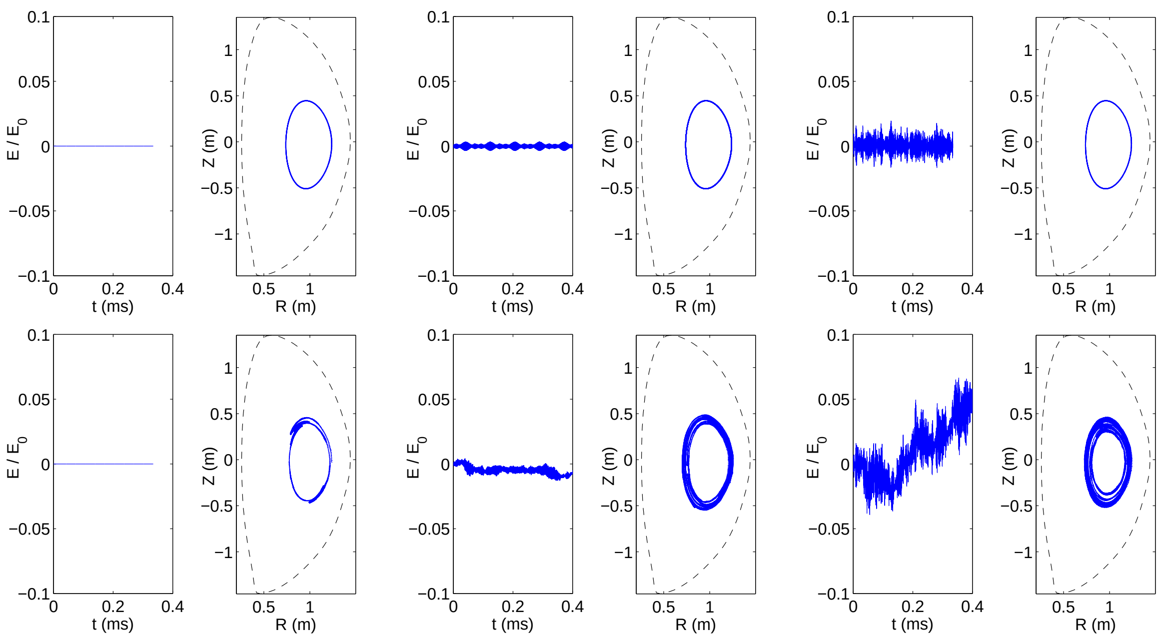

Figure 3: Energy history and spatial motion for six different one-particle simulations. Without collisions (top) and with collisions (bottom). No eigenmodes (left), 1 mode (middle) and 20 modes (right).

statistical spread of the final energies is large, so a Maxwellian with a low temperature of 200 eV is chosen for the results presented in the right plot in Figure 4. The heating is approximately proportional to the number of included eigenmodes, but this also depends on the order in which new eigenmodes are added.

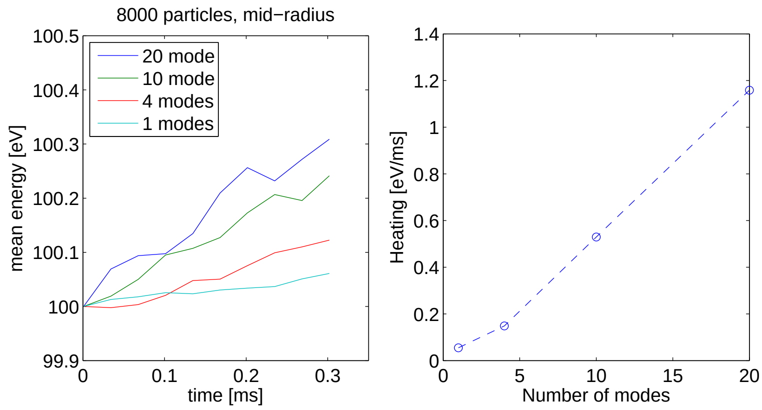

Figure 4: Left: Evolution of the mean energy of 8000 particles at mid-radius in eigenmodes with $\delta B/B \sim 2\cdot10^{-3}$. Right: Mean heating for 508000 particles, distributed over normalised radii r/a =0.1–0.7 and over 1–1000 eV, convoluted with a Maxwellian.

In these simulations the eigenmode amplitude was $\max(\delta B)/B_{\text{axis}} = 2\cdot10^{-3}$. From Figure 2 of Ref. [1] one can find that the heating is approximately proportional to the square of the mode amplitude. The typical mean square amplitude along a particle trajectory for the eigenmodes in these simulations is $\delta B^2/(\max(\delta B))^2 \sim 10^{-1}$. One should thus compare our result to the slab calculations of Ref. [1] (which were performed for 21 modes in a similar frequency range) for fluctuation amplitudes $\delta B/B \sim 6\cdot10^{-4}$. The slab results indicate a heating rate for these amplitudes of ~ 2 eV/ms, which is consistent with the value 1.2 eV/ms in the present calculations for 20 eigenmodes in Figure 4. Before we can assess if this mechanism can explain the observed heating, we need to obtain the experimental amplitudes from, e.g., the high-k diagnostic.

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