Modelling of TAE mode excitation with an antenna in realistic X-point geometry

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Introduction

In magnetic fusion devices, the excitation of Toroidal Alfven Eigenmodes (TAEs) [1] can be caused by fusion-born alpha-particles or fast ions generated by Ion Cyclotron Resonance and neutral beam heating. TAEs may affect fast particle confinement, reduce heating and current drive efficiency, cause damage to the first wall, and decrease overall plasma performance. In the absence of fast ions, TAEs can be investigated by launching electromagnetic waves by an external antenna, and sweeping the antenna frequency across TAE frequency range in order to detect a high-quality peak in the plasma response.

Excitation of TAE modes with an external antenna has been very successful [2]. It was shown, however, that TAEs, excited with an antenna, that are clearly visible in the limiter phase of the discharge disappear when the X-point forms, possibly due to an increase in the damping rates. More detailed investigations were performed in order to better understand the dynamics and damping mechanisms of global AE modes, e.g. [3] [4] [5]. These studies show that the damping rates increase significantly with shaping of the plasma and the gap between plasma and the external antenna, strongly depends on the variation of the plasma profiles at the edge, and is independent of the edge shear.

However, modelling with a realistic X-point representation has not been done yet. The aim of the present work is to investigate in detail the effect of the X-point geometry on the efficiency of the TAE excitation and the damping rate. Hence, in the course of this work an influence of the near-LCFS (Last Closed Flux Surface) layer from the core side on the damping of the TAE modes, and the difference between the damping in limiter and X-point geometries including the SOL with open field lines are investigated.

Dependence of the damping rate on the near-LCFS

The equilibrium produced by the EFIT code [6] from JET discharge #42870 during the X-point phase was used in this work. This discharge is from a dedicated TAE campaign on JET, during which a n=1 TAE mode was excited with a saddle coil. In the limiter phase, the TAE mode had a frequency of 150kHz and a normalized damping rate of $\gamma/\omega \approx 1.5\%$. However, after transition to an X-point configuration, no TAE modes were found.

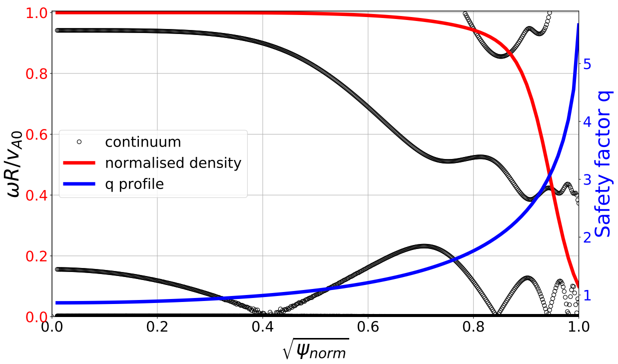


Figure 1: *Alfven continuum for n=1 mode, density and q profiles for a JET shot #42870 at t=54.88s.*

The equilibrium was analyzed with the CSCAS ideal MHD code [7] in order to calculate the radial structure of the n=1 Alfven continuum for given density, pressure, and q profiles (fig. 1). The TAE radial structure, frequency, and damping rate were modelled using the linear resistive MHD code CASTOR [8] with external antenna. CASTOR calculates the stationary state solution at a given antenna frequency. In the simulation a realistic Spitzer resistivity profile was used, and viscosity of the plasma is not taken into account.

It is important to note that CASTOR and CSCAS can model shaped equilibria, but cannot take into account the X-point due to the choice of the flux-surface coordinate system. Hence, the real equilibria have to be "cut" along a certain flux surfaces so that there are only closed field lines in the modelling domain. This maximal outermost flux surface taken into account (which will be called ψ_{max} in this work) can be chosen arbitrarily. Therefore, by varying $\psi_{max} = 0.95,...,0.995$ it is possible to evaluate the change of the TAE damping rate with plasma simulation boundary approaching the separtrix. For a fixed ψ_{max} the simulation with the CASTOR code was performed by sweeping the frequency of the applied antenna signal (fig. 2). This allows to obtain a response function with a Gaussian peak, and its FWHM characterizes the damping rate of the system, as illustrated in fig. 3.

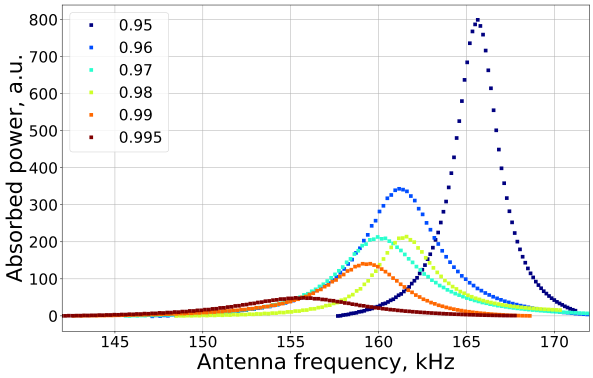


Figure 2: *Frequency scan as a function of* ψ_{max}.

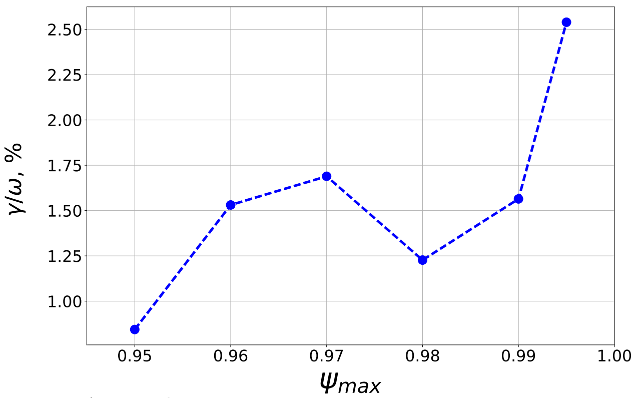


Figure 3: *Damping rate as a function of* ψ_{max}.

Calculated damping rates of 1-2.5% are consistent with experimental observations in this discharge. The sudden decrease in the damping rate for ψ_{max} increasing from 0.97 to 0.98 can be explained by the change of q profile: the maximal value of q changes from 4 to 5, therefore the mode structure and consequently frequency changes. As expected, the damping rate increases when approaching the separatrix. This result indicates that one aspect of the difficulty of excitation of the TAE modes in X-point geometry is an increased damping from the region inside the separatrix.

TAE excitation in X-point geometry

The JOREK-STARWALL nonlinear MHD code has been extended to include active coils [9], which allows the simulation of the excitation of TAE modes with an external antenna in full X-point geometry, including the scrape-off layer, contrary to the results obtained with the CASTOR code where the X-point geometry can be only closely approximated. The plasma-vacuum-antenna system is evolved in time until a stationary state is obtained which typically requires 10^3 Alfven times.

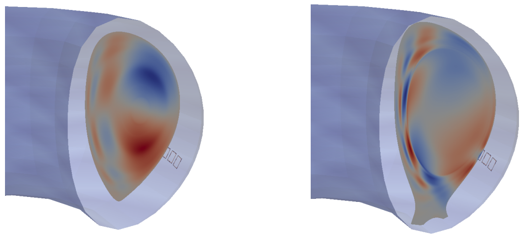
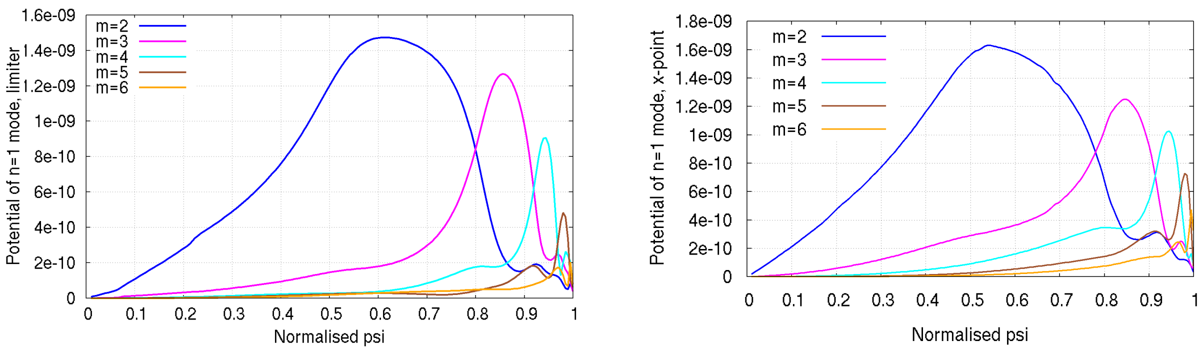


Figure 4: *Poloidal cross-section of the JOREK simulation in limiter and X-point geometry. Color corresponds to the electric potential of the n=1 mode.*



a. b.

Figure 5: *Radial mode structure for n=1 mode of the electric potential for a (a.) limiter case at frequency* $f = 172kHz$ *(b.) X-point case at frequency* $f = 154kHz$.

The simulations of antenna excitation of TAE modes is challenging due to the low dissipation (i.e. resistivity, viscosity) that is required to avoid artificially strong damping, and existence of induced currents in the domain boundary which screens part of the antenna signal. In order to isolate a specific effect of the presence of the scrape-off layer (SOL) the initial equilibrium was analyzed in two ways. In the first case the plasma boundary was set at the flux surface $\psi_{norm} = 0.999$, and in the second case the whole equilibrium with a real X-point including the SOL was taken, as shown in fig. 4. The n=0 mode of the equilibrium and initial profiles are kept constant throughout the simulation for both cases.

In both cases TAE peaks are found which are split into a main resonance and a smaller peak just below the continuum. The main resonance frequencies are $f_{1lim} = 172kHz$ and $f_{1x\text{-}point} = 154kHz$ for the limiter and X-point case respectively, while the secondary peaks have a frequency of $f_{2lim} = 206kHz$ and $f_{2x\text{-}point} = 205.5kHz$. The mode structures for the limiter case at frequency $f_{1lim} = 172kHz$ and X-point case at frequency $f_{1x\text{-}point} = 154kHz$ are shown in fig. 5

a. and b. respectively. The damping rates of corresponding TAE peaks are 2.5% for the limiter case and 7% for the X-point case. Results in a limiter plasma with the time evolution code JOREK-STARWALL are in good agreement with the steady state solution from CASTOR.

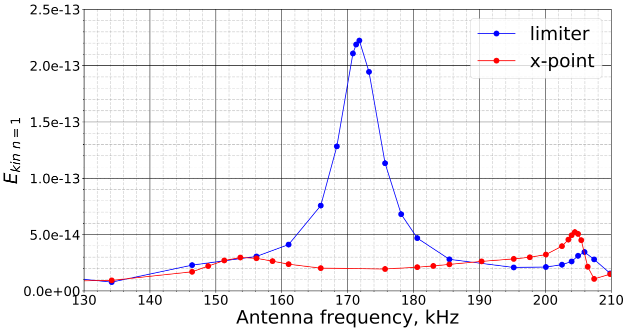


Figure 6: *Frequency scan for the limiter geometry – blue line; the X-point geometry – red line.*

A clear cause of the increase of the damping in the presence of X-point cannot be definitely identified. A possible explanation of the increased damping in the SOL is existence of an Alfven continuum on the line-tied open field lines in analogy to what was proven to exist in [11] for coronal loops, which could cause the continuum damping of the mode in the SOL. This idea can be supported by an experimental result demonstrated in [10] where observed damping rates increased with increase of the gap between a plasma and antenna. However, this hypothesis requires a further investigation.

Conclusions

In this work, the effect of the presence of the X-point and SOL on the excitation efficiency of the TAE modes was investigated. Two effects which cause increase of the damping rate were identified. Results obtained with linear resistive MHD code CASTOR show a clear trend of increase of the damping rate with the plasma boundary approaching the separatrix. The simulation of TAE mode excitation by an external antenna in JOREK-STARWALL has been demonstrated with results consistent with linear code CASTOR. The results show that the dominant effect of the increased damping of TAE modes in X-point geometry is due to the presence of the the SOL.

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