# Numerical investigation of fast-ion-driven modes in Wendelstein 7-X

C. Slaby[1], A. Könies[1], R. Kleiber[1], S. Äkäslompolo[1], and J. Kontula[2]

[1] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[2] *Aalto University, Aalto, Finland*

## Introduction

Heating methods such as neutral beam injection (NBI) or ion cyclotron resonance heating (ICRH) generate fast ions in fusion plasmas. In order to effectively heat the plasma, the fast ions need to remain confined for a time period on the order of the slowing-down time. While slowing down, the fast ions may resonantly interact with Alfvénic perturbations, which can lead to enhanced fast-ion transport [1] and premature ejection of fast ions from the plasma.

Here, we numerically investigate the interaction of Alfvén waves and fast ions in a Wendelstein 7-X (W7-X) high-mirror configuration. Note that one of the optimization goals of W7-X is good fast-ion confinement [2].

The simulations are performed using the non-linear CKA-EUTERPE code package [3]. It combines the ideal MHD code CKA, which provides a mode structure, and the gyro-kinetic code EUTERPE, which computes the power transfer from the fast ions to the mode. This approach is perturbative since the mode structure remains fixed for the entire calculation.

Even though non-linear simulations, using CKA-EUTERPE, have been conducted in the past for W7-X [4], this is the first time that a realistic fast-ion distribution function and density profile, as expected for plasmas in operation phase 1.2b (July-October 2018), are considered. Both are obtained using the ASCOT code [5, 6]. As can be seen in Fig. 1 (top), we use a slowing-down distribution function with two intermediate steps to describe the fast ions. Those steps are at $E_{\max}/2$ and $E_{\max}/3$ and come from the acceleration of molecular hydrogen. The black circles are computed by ASCOT while

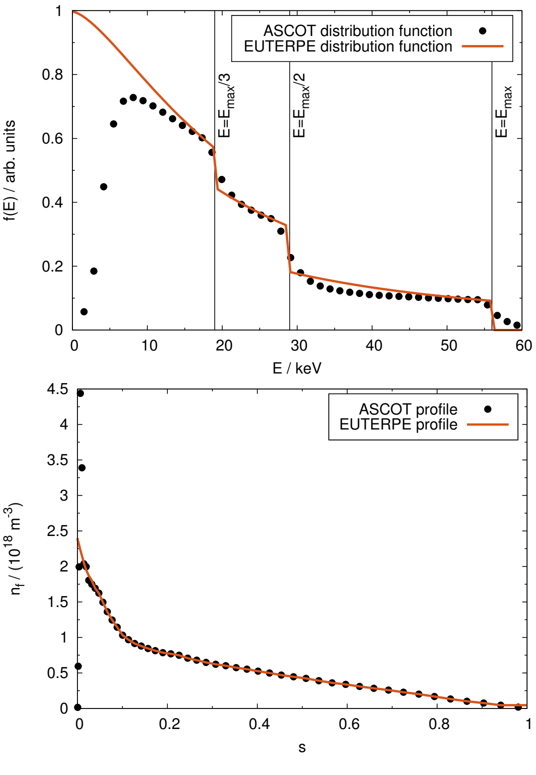

*Figure 1: Fast-ion distribution function (top) and density profile (bottom) provided by ASCOT (black dots) and used in EUTERPE (red line).*

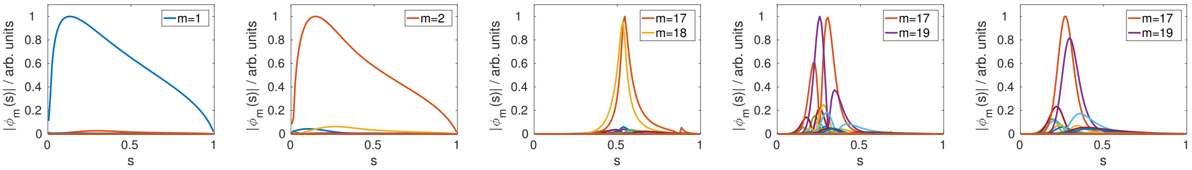

*Figure 2: Alfvén eigenmodes found in the W7-X high-mirror configuration. From left to right: GAE ($m = 1; n = -1$), GAE ($m = 2; n = -2$), TAE ($m = 17, 18; n = -16$), even EAE ($m = 17, 19; n = -16$), odd EAE ($m = 17, 19; n = -16$).*

the red line is the fit that is used in EUTERPE. The distribution function provided by ASCOT is non-uniform in the pitch-angle variable $\xi = v_{\|}/v$. For our EUTERPE simulations, on the other hand, a uniform distribution is used as a first approximation. The generalization to a pitch-angle-dependent distribution function is straightforward and will be reported elsewhere.

The fast-ion density profile used in all simulations is shown in Fig. 1 (bottom). The density gradient provides the source of free energy that can potentially drive Alfvén eigenmodes (AEs) unstable. Note that the density profile computed by ASCOT is noisy close to the magnetic axis. Therefore, the density profile is smoothed for usage in EUTERPE. Since the AEs that will be studied later are localized at larger radii (see Fig. 2), it is a reasonable assumption that the growth rates are independent of the exact shape of the density profile in the core of the plasma.

The profiles of the background plasma are determined by NTSS [7] calculations. The on-axis values $n_{\mathrm{i},0} = n_{\mathrm{e},0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3}$ (hydrogen), $T_{\mathrm{i},0} \cong 2.5$ keV, $T_{\mathrm{e},0} \cong 4.5$ keV are close to the parameters envisaged for W7-X OP 1.2b plasmas where NBI will be available.

## Eigenmodes found by CKA

Several AEs – possible candidates for the destabilization by fast ions – are found in this W7-X high-mirror configuration using CKA. The radial mode structures (indicating also the mode numbers) are shown in Fig. 2. Of lowest frequency are two global Alfvén eigenmodes (GAEs) that fulfil $|m| = |n|$. Therefore, they are classified as so-called isomon modes [8]. At higher frequencies, a toroidicity-induced Alfvén eigenmode (TAE) and two ellipticity-induced Alfvén eigenmodes (EAEs) are found by CKA. All these AEs are located at different radial positions and have different frequencies. It is therefore expected that they will react differently to the fast-ion drive. The

*Table 1: Frequencies and linear growth rates of the Alfvén eigenmodes shown in Fig. 2.*

| | $\omega/\mathrm{s}^{-1}$ | $\gamma_\mathrm{L}/\mathrm{s}^{-1}$ |
|---|---|---|
| $m = 1$ GAE | $2.772 \cdot 10^5$ | $1.149 \cdot 10^3$ |
| $m = 2$ GAE | $3.029 \cdot 10^5$ | $2.505 \cdot 10^3$ |
| TAE | $4.436 \cdot 10^5$ | $1.008 \cdot 10^3$ |
| even EAE | $8.306 \cdot 10^5$ | $5.033 \cdot 10^2$ |
| odd EAE | $8.522 \cdot 10^5$ | $5.852 \cdot 10^2$ |

mode frequencies $\omega$ and growth rates $\gamma_{\mathrm{L}}$ obtained from a linear calculation are listed in Tab. 1. Since the growth rate is predicted to scale as [9, 10]

$$\gamma_{\mathrm{L}} \sim m\frac{\omega_\star}{\omega} - 1, \tag{1}$$

where $\omega_\star$ denotes the diamagnetic drift frequency of the fast ions, it is not surprising that modes at higher frequency have a smaller linear growth rate. Finite-Larmor-radius effects reduce the growth rate and become more important for high-$m$ modes.

## Non-linear results

In order to numerically determine the saturation levels of the modes in non-linear calculations, a damping rate $\gamma_{\mathrm{d}}$ must be present. For $\gamma_{\mathrm{d}} = 0$, a sub-exponential drift after the initial linear phase is observed. Note that in CKA-EUTERPE, $\gamma_{\mathrm{d}}$ is an externally specified parameter.

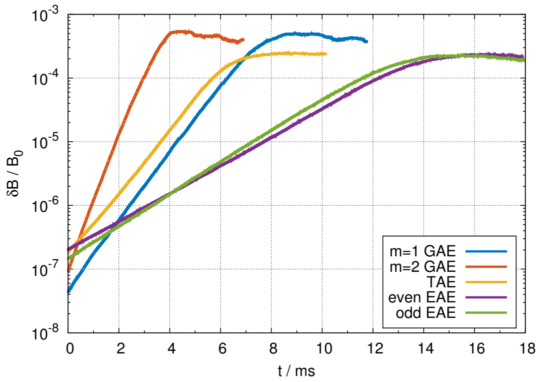

*Figure 3: Time traces of the perturbed poloidal magnetic field associated with the modes shown in Fig. 2. The non-linear simulations include a fast-ion collision operator.*

Since the growth rates of the modes are small, and still we want to save computation time, the following approach is pursued: We artificially increase the growth rate by a factor $\alpha > 1$. We then specify a damping rate $\gamma_{\mathrm{d}} = (\alpha - 1)\gamma_{\mathrm{L}}$, such that $\alpha\gamma_{\mathrm{L}} - \gamma_{\mathrm{d}} = \alpha\gamma_{\mathrm{L}} - (\alpha - 1)\gamma_{\mathrm{L}} = \gamma_{\mathrm{L}}$ is the original linear growth rate. For practical purposes, $\alpha = 5.5$ has been chosen. Since the physical damping rate is missing, this approach corresponds to a maximal estimate of the saturation levels.

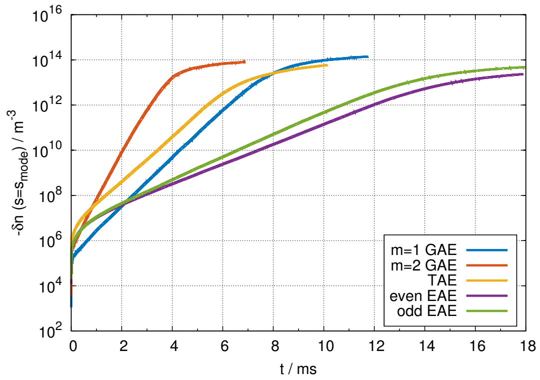

*Figure 4: Change of the fast-ion density profile at the radial positions where the modes shown in Fig. 2 have their respective maximum.*

Fig. 3 shows the time traces of the perturbed poloidal magnetic field associated with the mode. A fast-ion collision operator was present in the numerical simulations, since collisions play an important role in the formation of the distribution function and can also influence the non-linear dynamics of AEs [4]. At $s = 0.5$, the critical velocity and slowing-down time are $v_{\mathrm{c}} \cong 2.23 \cdot 10^6$ m/s and $\tau_{\mathrm{s}} \cong 60$ ms, respectively. All modes saturate in the range of $\delta B/B_0 = 10^{-4} - 10^{-3}$.

The modes cause radial transport of fast ions as is indicated in Fig. 4. The flattening of the fast-ion

density profile is on the order of $\delta n \cong -10^{14}\ \mathrm{m}^{-3}$
at the maximum position of the mode and thus four orders of magnitude lower than the value of the fast-ion density profile at this point. Higher saturation levels lead to an increased fast-ion transport. A similar observation has been made in Ref. [4].

So far only the drive of the modes due the presence of fast ions has been addressed. However, to make a prediction whether the modes will be unstable in the experiment requires also knowledge of the damping rates. The radiative damping rates of the gap modes have been estimated using the reduced model of STAE-K [10]. The GAEs cannot be addressed using STAE-K. For the TAE we find $\gamma_{\mathrm{d}}/\omega = -6\%$. The even and odd EAEs have lower normalized damping rates of $-0.7\%$ and $-0.5\%$, respectively. In any case, the damping rate exceeds the linear growth rate which means that, for the case studied, the fast-ion drive is likely not sufficient to destabilize gap modes.

## Summary

We have investigated possible fast-ion driven modes in a Wendelstein 7-X high-mirror configuration for plasmas expected in the up-coming operation phase 1.2b.

Of all AEs investigated here the GAEs have the highest saturation levels and normalized growth rates. Our results are in agreement with the value of $\gamma_{\mathrm{L}}/\omega = 10^{-3} - 10^{-2}$ given in Ref. [8]. Due to their radially extended mode structure, they might be the easiest to be excited by fast ions. In order to predict which modes will be unstable in the experiment, more work is needed to accurately compute damping rates.

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## References

[1] H. H. Duong *et al.*, Nucl. Fusion **33**, 749 (1993)

[2] G. Grieger *et al.*, Phys. Fluids **B** (7), 2081 (1992)

[3] T. B. Fehér, Ph.D. thesis, University Greifswald, 2013

[4] C. Slaby *et al.*, Nucl. Fusion, accepted (2018)

[5] J. A. Heikkinen, S. K. Sipilä, Phys. Plasmas **2**, 3724 (1995)

[6] E. Hirvijoki *et al.*, Comp. Phys. Comp. **185**, 1310 (2014)

[7] Y. Turkin *et al.*, Phys. Plasmas **18**, 022505 (2011)

[8] Ya. I. Kolesnichenko *et al.* Nucl. Fusion **56**, 066004 (2016)

[9] G. Y. Fu *et al.*, Phys. Fluids **B** (11), 3722 (1992)

[10] C. Slaby *et al.*, Phys. Plasmas **23**, 092501 (2016)