Energetic particle driven instabilities during the L-H transition in ASDEX Upgrade

Ph. Lauber[1], V.-A. Popa[1], T. Hayward-Schneider[1], M. Falessi [2], G. Tardini [1], M. Weiland[1], Eurofusion ENR ATEP[3] and the ASDEX Upgrade Team

[1] *Max-Planck-Institut für Plasmaphysik, IPP, Germany*
[2] *ENEA, Fusion and Nuclear Safety Department, Frascati (Roma), Italy*
[3] *see ENR ATEP Team: https://wiki.euro-fusion.org/wiki/Project_No10*

Abstract

Reduced models for predictive transport studies that include instabilities driven by energetic particles (EPs) require - even in the quasi-linear limit - a global, kinetic and electromagnetic analysis. In this paper the automated EP-Stability IMAS Workflow based on the LIGKA code [1, 2] is used to analyse EP-driven instabilities in a slow L-H transition at ASDEX Upgrade [3]. Local and global properties of a prominent toroidal Alfvén eigenmode are determined for more than 100 time slices with a resolution of a few milliseconds. The infamous sensitivity of the damping rates on the plasma background profiles can be assessed and quantified using this procedure. Scans with high radial resolution allow us to constrain the properties of edge-localised Alfvénic activity.

Introduction

Traditional experiments on present day devices face the difficulty that the redistribution of energetic particles (EPs) due to instabilities in the low-toroidal-mode number regime lead either to substantial losses or to a redeposition of EPs close to the plasma edge where the slowing down times decrease considerably, and other transport effects such as 3D perturbations are present.This means that the influence of the redistributed particles on the background plasma is usually negligible and not measurable. This will be different in burning plasma experiments at ITER, where redistributed EPs by core-localised instabilities are expected (and required) to be well-confined, broadening the alpha-particle heating profile. Depending on the intermittency of the core-transport mechanisms, interesting multi-time-scale self-organisation processes may be expected.

This paper reports experiments on ASDEX Upgrade (AUG) trying to mimic part of the physics described above. In order to avoid the complications due to edge losses, an off-axis-peaked EP distribution is generated by NB-heating, leading also to inwards- directed EP transport. Since the investigated discharge features a slow L-H transition, it is an ideal candiate for a time-dependent analysis for mode properties and EP transport characteristics. For this reason, this discharge will be part of a larger V&V effort carried out within the Eurofusion theory projects TSVV#10[4] and ENR ATEP[5].

Observations

Discharge #39681 was carried out in the hydrogen campaign 2021 with $B = -2.2T$ and $I_p = 700$kA. 5MW NB-heating using source 6 and 7 (using deuterium) was applied as shown in fig. 1. On-axis 15ms beam blips (source 3) allow us to measure ion temperature and rotation. After the ramp up phase, a relatively stable L-mode phase from 2-3s can be observed. Due to the exclusive off-axis heating and the ramp-up characteristics, core impurities keep electron and ion temperatures relatively low and even slightly inverted (see fig 1). The ratio of maximal beam energy (93keV) and background ion temperature is 60-90. Due to the off-axis current drive, the q-profile is inverted with $q_{min} \sim 2.5$ at mid-radius.

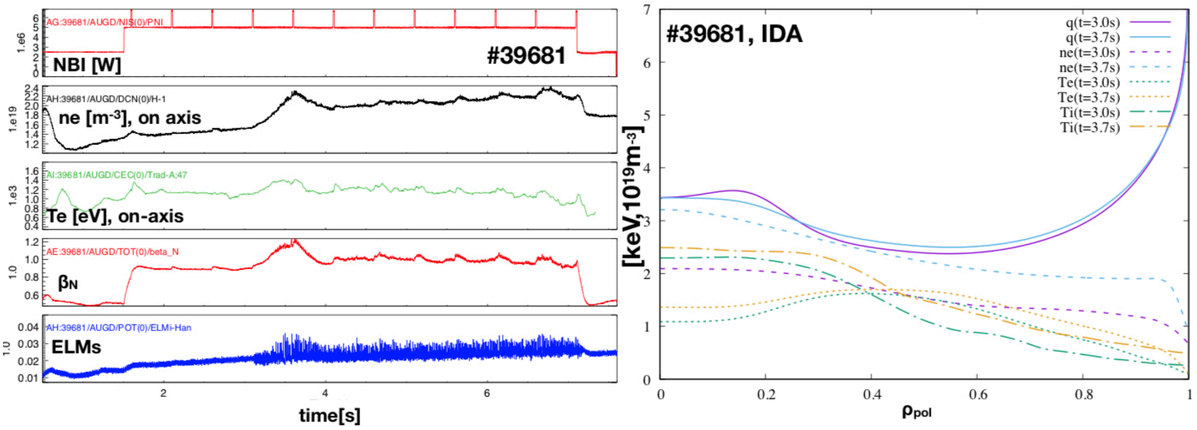

Fig. 1: *Left: time traces of some key quantities of AUG discharge* #39681*; Right: radial profiles of safety factor q, ion and electron temperatures and density at the time points* $t_1 = 3.0s$ *and* $t_2 = 3.7s$ *(start and end of L-H transition). IDA-calculated uncertainties are available for all profiles, but not plotted here.*

Note that due to the higher L-H transition threshold in hydrogen plasmas 5MW are not enough at this low density to transition into H-mode. At 3s, a beam blip and together with a slow rise in density triggers a slow transition that causes small ELMs and a density pedestal (see fig 1).

Modes with positive mode numbers in fig. 3 are driven by the positive radial EP gradient, propagating in the electron diamagnetic direction. An $n = 2$ TAE (toroidal Alfvén eigenmode, yellow color) is the most prominent mode observed. Also TAEs between $150-200$kHz propagating in the ion diamagnetic direction (blue, violet) are observed. At 3.7s the appearance of the $q = 2.5$ surface leads to a pressure driven kink mode with $n = -2$ and its harmonics at 20kHz. Interestingly, also a prominent $n = -2$ magnetic perturbation at 300kHz is observed in the L-mode phase. As can be seen in fig. 2, this mode jumps during the start of the L-H transition from 300 to 340kHz and then disappears (see also fig 3). Comparing the relative amplitude evolution of the magnetic perturbations on low-field-side and high-field-side reveals that the mode changes its character from predominantly ballooning ($t < 3.12s$, barley visible in high-field side coils) to non-ballooning ($t > 3.12s$, clearly visible in both high- and low-field side coils). Also, this mode is visible in almost all soft X-ray channels, indicating that the mode is edge localised.

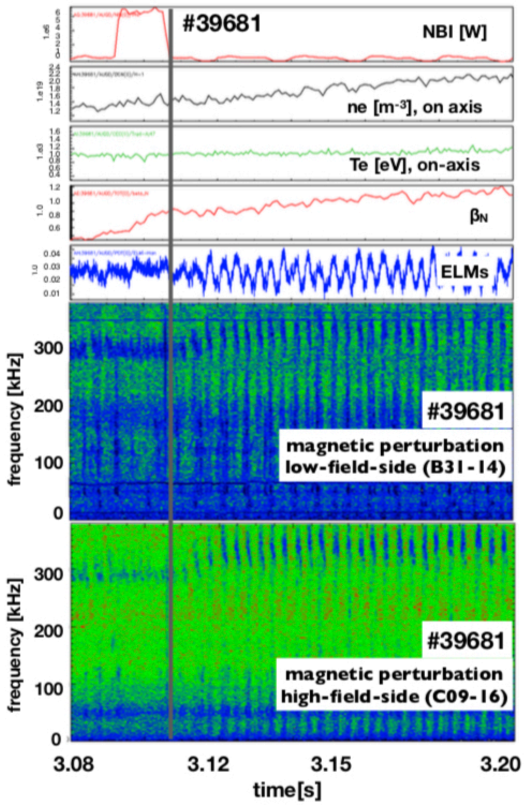

Fig. 2: *Time traces and spectrograms of the magnetic perturbations for the initial transition phase, details in the text*

Modelling

The phase between $t = 3s$ and $t = 3.8s$ is modelled with the recently developed Energetic Particle Stability Workflow (EP-WF) [6], based on IDA data [7] and the AUG-IMAS interface TRVIEW [8]. All simulations are carried out fully within the IMAS environment on the Eurofusion Gateway computer system. High-resolution equilibrium reconstruction, local and global linear gyro-kinetic LIGKA runs are automatically performed for 160 time slices during the transition. The results are summarised in fig 3. Both local and global frequencies and damping rates are determined for the counter-propagating $n = 2$ TAE, and also the reduced MHD and kinetic continua (here just shown for the last time point) were calculated. On the bottom right, the global mode structure together with the parallel electric field is given. (An animated gif for all time slices can be found following ref. [9]. Due to temporary technical limitations, the IMAS database contains only one ion species, i.e. hydrogen. Since the NB beam injection adds a significant D fraction the Alfvén velocity has to be adjusted when comparing the modeling results with the experiment. From NPA and spectroscopic measurements the D fraction is determined to be $35-45\%$. Together with the estimate $Z_{eff} = 1.4$ and using an average impurity charge and mass of carbon, this gives using $n_D = n_e - n_H$ for $v_{A,H}/v_{A,HD} = \sqrt{1-n_D/n_e + m_C/m_H \cdot n_C/n_e} = 1.25$. The rotation is measured to be roughly $7kHz$ at the location of the TAE, meaning that the Doppler shift for the experimentally measured $120kHz$ TAE with $n = 2$ leads to $134kHz$ in the plasma reference frame (note that the Doppler shift has to be added here, since mode propagation direction and plasma toroidal rotation are in opposite directions). Taking the correction for the Alfven velocity into account leads to $165kHz$. This does not match the theoretically calculated $f_{TAE} = 152kHz$. However, uncertainties in the plasma composition at the TAE location (measurements above are line averaged quantities) can easily lead to a better agreement. E.g. assuming 20% of D, would lead to a reasonable match. This type of Alfvén spectroscopy can be very useful for multi-component plasmas such as burning plasmas. Further, using the uncertainty information already provided naturally by the IDA approach, will also allow us to systematically quantify the other typical measurement and equilibrium reconstruction errors in a rigorous and transparent way.

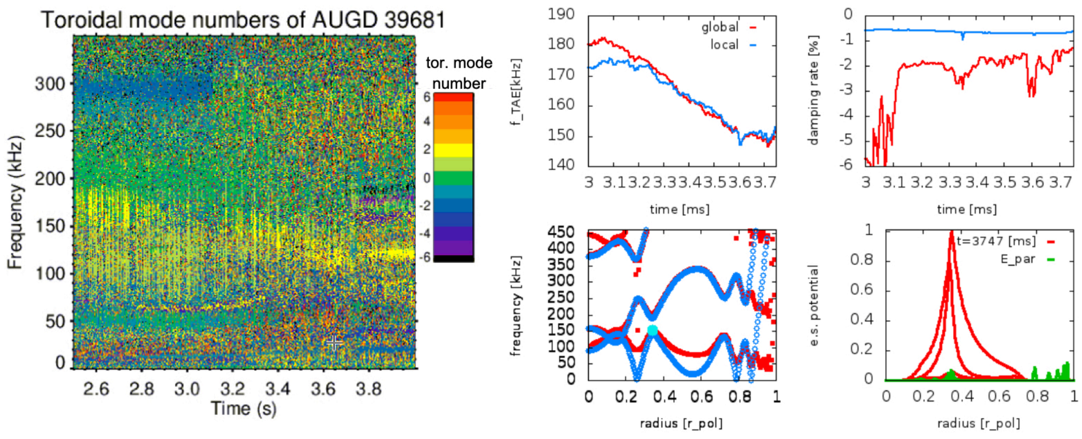

Fig. 3: *Left: toroidal mode number spectrum as measured by the magnetic pick-up coils during an L-H transition (∼3.0-3.8s) for AUG discharge #39681. Right: the results of the EP-stability workflow for the toroidal mode number n = 2, summarising local and global mode frequency (top left), damping rate (top right) as a function of time, MHD and kinetic continuous spectra (bottom left, with TAE gap marked in light blue) and global mode structures of electrostatic potential (two main pol. harmonics) and parallel electric field for the last time point of this series of linear runs.*

In order to narrow down the reason for the evolution of the $n = -2$ mode at $300kHz$, a radially high-resolved continuum calculation is carried out. It becomes clear that 300 and 340 kHz modes would reside in the ellipticity induced AE gap, crossing the continuum to the TAE gap at around $\rho_{pol} = 0.72$ (see fig 4). Comparing two snapshots at times $t_1 = 3.00$ and $t_2 = 3.15$ shows that the $n = -2$ shear Alfvén and also kinetic continua are not changing significantly during the first transition phase. Note that the narrow region $\rho_{pol} > 0.99$ is well resolved and the EAE gap at the edge does not open for $n = -2$ during the the time under consideration, meaning that the continuum damping in this region is not changing significantly. Estimating the transit time for the fastest NB particles reveals that only very high order resonances (> 5) would fulfil the EAE resonance condition, leading to a very inefficient NB drive that cannot overcome the damping rates ($\sim 0.5\%$). Therefore, we assume that the mode must be driven non-linearly by the underlying drift wave turbulence [10]. Using the global solver, two weakly damped EAEs for the times t_1 and t_2 were added to fig. 4, showing that at the experimentally projected frequencies (using the same corrections for v_A and f_{rot} as described above), the global Alfvénic modes move slightly inwards between t_1 and t_2. However, the parity of the modes is not changing, therefore the experimental indications of a change in the ballooning structure cannot be explained with this linear calculation. Interestingly, only $n = -2$ can be observed, although also other low-n gaps would have very similar continua and damping characteristics.

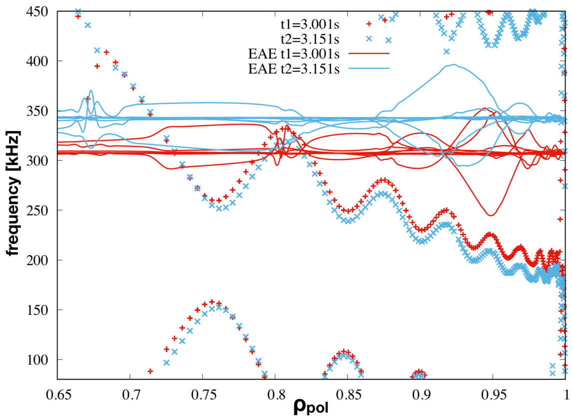

Fig. 4: *Kinetic continua for $n = -2$ before and after the first phase of the LH transition $t_1 = 3.00s$ and $t_2 = 3.15s$. Corresponding weakly damped EAE mode structures are added at their respective mode frequencies.*

Conclusions

The automated local and global stability analysis of many time slices from an experiment can be used for a more comprehensive and reliable analysis of the observed instabilities. Obviously single time slices still show a very sensitive dependence of the damping rates on profiles and equilibria, but the underlying trends can be captured very reliably. Also, the limits of linear analyses can be easily determined, guiding future non-linear simulations.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

[1] Ph. Lauber, S. Günter, A. Könies, and S.D. Pinches. LIGKA: A linear gyrokinetic code for the description of background kinetic and fast particle effects on the MHD stability in tokamaks. *Journal of Computational Physics*, 226(1):447 – 465, 2007.

[2] V.-A. Popa. Workflow-based energetic particle stability analysis of projected ITER plasmas. *Master Thesis, TU München*, 2020.

[3] see author list of U. Stroth et al. 2022 Nucl. Fusion 62 042006.

[4] Eurofusion TSVV#10 team (P.I. A. Mischchenko). 2021.

[5] Eurofusion Enabling Research ATEP Team (P.I. Ph. Lauber). 2021.

[6] Popa V.-A. et al. *Presented at the 4th IAEA TCM on Fusion Data Processing (online meeting, Dec 2021)*, 2021.

[7] R. Fischer, L. Giannone, J. Illerhaus, P. J. McCarthy, R. M. McDermott, and ASDEX Upgrade Team. Estimation and uncertainties of profiles and equilibria for fusion modeling codes. *Fusion Science and Technology*, 76(8):879–893, 2020.

[8] G. Tardini https://www.aug.ipp.mpg.de/aug/manuals/transp/trview/index.html. 2022.

[9] Ph. Lauber https://pwl.home.ipp.mpg.de/. 2022.

[10] M. Maraschek, S. Günter, T. Kass, B. Scott, H. Zohm, and ASDEX Upgrade Team. Observation of toroidicity-induced alfvén eigenmodes in ohmically heated plasmas by drift wave excitation. *Phys. Rev. Lett.*, 79:4186–4189, Nov 1997.