Alfvén-wave character oscillations in tokamak COMPASS plasma

T. Markovič[1,2], J. Seidl[1], A. Melnikov[3,4], P. Háček[1,2], J. Havlicek[1,2], A. Havránek[1,5], M. Hron[1], O. Hronova[1]. M. Imríšek[1,2], F. Janky[1], K. Kovařík[1,2], O. Mikulín[1], R. Pánek[1], R. Papřok[1,2], J. Pipek[1], P. Vondráček[1,2], V. Weinzettl[1]

[1] *Institute of Plasma Physics CAS, Prague, Czech Republic*

[2] *Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic*

[3] *National Research Centre 'Kurchatov Institute', Moscow, Russian Federation*

[4] *National Research Nuclear University MEPhI, Moscow, Russian Federation*

[5] *Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

In magnetic confinement fusion devices, high-energy particles originating e.g. from auxiliary-heating systems can drive instabilities by channeling the free energy (typically pressure gradients) to otherwise stable plasma eigenmode via resonance of particle velocity with plasma Alfvén velocity [1]. Consequently, the confinement of these particles is degraded by their interaction with the resulting shear Alfvén waves. Toroidal Alfvén Eigenmodes (TAE), caused by an interference of two counter-propagating Alfvén continuum waves [2], are of the most concern due to their low damping rate. In the recent work from the COMPASS tokamak [3], observations of possible TAE and BAE (Beta-induced Alfvén Eigenmodes) in H-mode plasmas in the spectral range of 50-250 kHz were reported. The present work introduces further observations of plasma fluctuations in the spectral range of 150-2500 kHz in both L-mode and H-mode plasmas showing their Alfvén-wave character.

Experimental arrangement

The COMPASS tokamak is a device with an ITER-like plasma geometry, having major radius $R_0 = 0.57$ m and minor radius about 0.2 m. In discharges described in this work, plasma current was $I_p < 0.3$ MA, toroidal magnetic field $B_0 = 1.15$ T and pulse duration $\Delta t < 0.4$ s. The tokamak is capable of H-mode plasma generation, either ohmic or NBI assisted (2×300 kW deuterium beams, energy up to 40 keV). It is also equipped with a Resonant Magnetic Perturbation (RMP) system of variable spatial configuration [4]. Plasma eigenmode fluctuations are detected by two sets of Mirnov Coils (MC, 24 coils each) located at different toroidal positions measuring poloidal magnetic field fluctuations across the whole poloidal cross section (specifically, as coherence between two coils at the same poloidal position from different toroidal sets). Other detection coils are mounted on the U-probe manipulator [7] located in the bottom part of the chamber on Low-Field Side (LFS). The maximal detectable frequency is given by f_{Nyquist}

of used data acquisitions, i.e. 1 MHz for MC coils and 2.5 MHz for U-probe coils, respectively.

Frequency dependence on plasma parameters

The first indication that observed oscillations have Alfvén wave character comes from a scaling of their frequency with global plasma parameters. An approximate spectral position of the center of the Alfvén-continuum gap is described in [2, 5]. In the scope of this work, a simplified scaling based on measured plasma parameters was used:

$$f_A(t) \sim \frac{B_0(t)}{q_{95}(t)\sqrt{n_e(t)}}, \qquad (1)$$

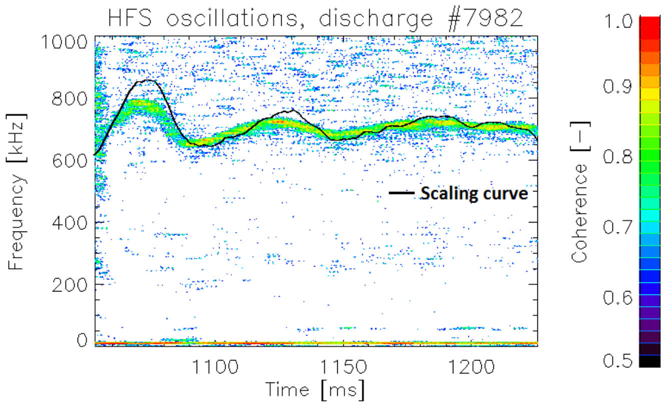

Figure 1: *High-frequency plasma oscillations on HFS during L-mode phase. Signal represents coherence between two selected MC coils. Black line represents eq. (1).*

with n_e being line-averaged electron density and q_{95} edge plasma safety factor. Experiments with ramps in each of these three parameters, as well as discharges featuring n_e oscillations, have shown that high-frequency High-Field Side (HFS) oscillations typically follow eq. (1) in both limited and diverted plasmas (with some abberation at higher densities) – see Fig. 1. During H-mode phase, the trend of fluctuation frequencies is slightly different from the scaling, which is most likely attributed to changes in a plasma profile.

Travelling wave character

Alfvén waves are detected as high-frequency fluctuations due to high velocity at which they travel along helical field-lines of the confining field. In laboratory reference frame, plasma rotation attributes as a Doppler shift correction [6]:

$$f_{\mathrm{tot}}(r) = f_A(r) + n \cdot f_{\mathrm{plasma}}(r), \qquad (2)$$

where n is toroidal mode number (periodicity) of the oscillation and f_{plasma} is frequency of plasma toroidal rotation at

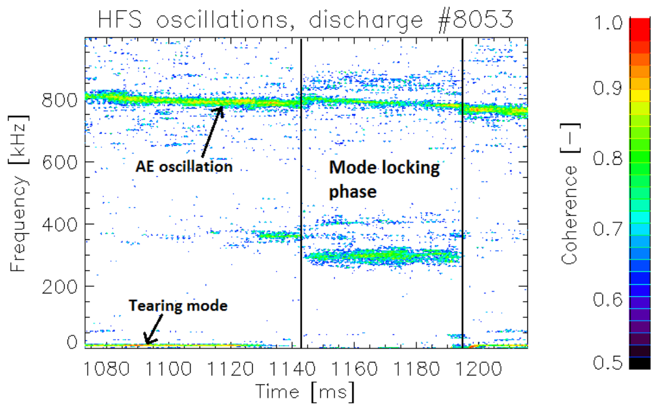

Figure 2: *High-frequency plasma oscillations on HFS. Signal represents coherence between two selected MC coils. Black lines show the start and the end of period in which mode locking occured.*

corresponding position. In the first approximation, rotation of low-frequency MHD instabilities of tokamak plasmas, e.g. tearing modes or kink modes, is fully attributed to the Doppler shift term. An interaction of magnetic islands with DC RMP field can cause radially localized braking of plasma rotation effectively mitigating the Doppler shift.

During mode locking phases of RMP discharges, it was seen that high-frequency oscillations localized on HFS persist, suggesting that these fluctuations are travelling-wave character shear Alfvén waves. This can be seen in Fig. 2, where the 800 kHz mode retains its frequency even after the 10 kHz tearing mode oscillation vanishes. Nevertheless, due to lack of rotation measurements, there is still some uncertainty in the radial extent of rotation braking that takes place, as well as in radial position of the studied high-frequency oscillation.

Oscillations correlated with runaway electrons

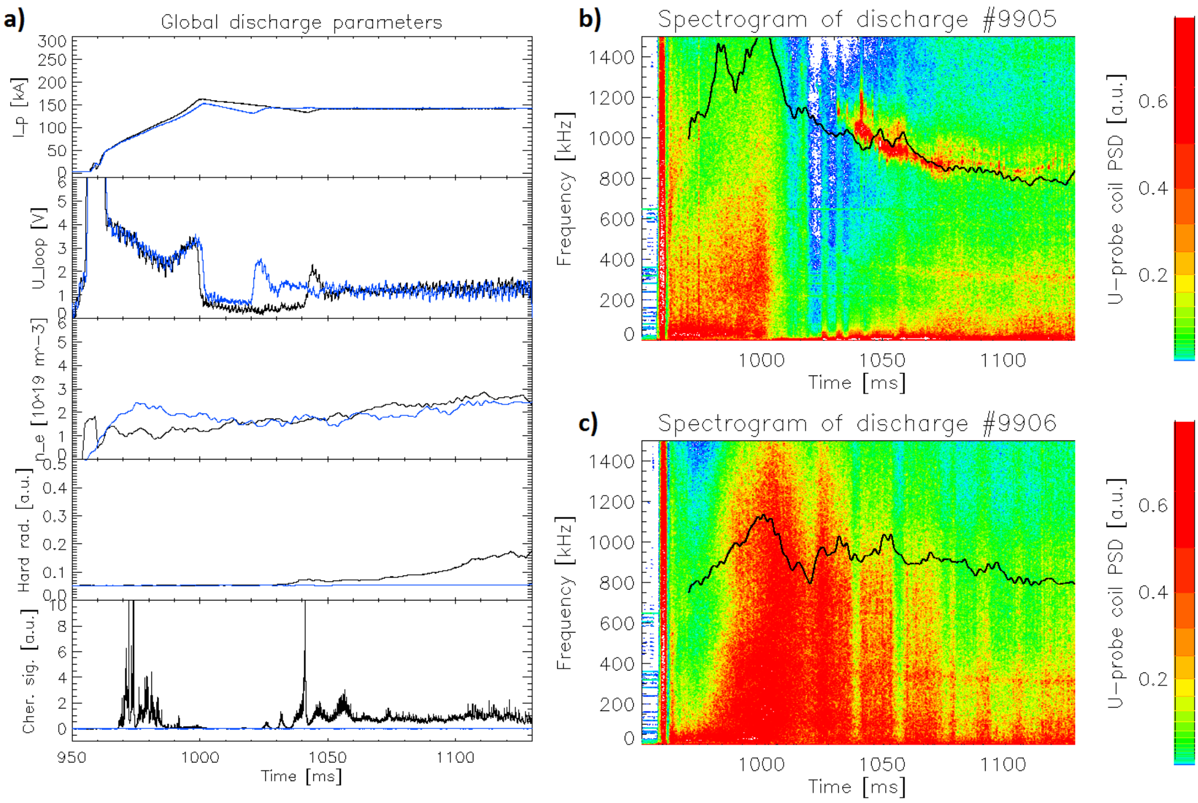

Figure 3: *a) Global parameters of shots no. 9005 (black) and no. 9906 (blue).* I_p *– plasma current,* U_{loop} *– loop voltage,* n_e *– line-averaged electron density, Hard radiation – photo-neutron detector signal, Cher sig. – Cherenkov detector measuring lost electrons at 50-260 keV energies on LFS. b) Spectrogram of U-probe coil signal on LFS for shot no. 9905 with scaling curve from eq. (1). c) The same graph as b) for shot no. 9906.*

In the previous work done on COMPASS [3], a possible involvement of runaway electrons in driving observed plasma fluctuations was discussed. Although a subsequent investigation of discharges with high U_{loop} and low n_e (hence with increased runaway electron population) did not show any straightforward indications for modes described up to this point, a new type of very high-frequency oscillations (up to f_{Nyquist} = 2.5 MHz) was observed. This tends to have a chirping character with frequency generally following eq. (1). Fig. 3 a) shows two identical discharges, the shot no. 9906 has a stronger gas puff during a plasma start-up phase than the one of no. 9905 – see the difference in n_e there. The runaway seed was affected and hence production of runaway electrons mitigated, as it can be seen from the different behavior of both hard radiation and Cherenkov detector signals. The spectrogram in fig. 3 b) shows 0.8-1.2 MHz oscillation, whose frequency follows eq. (1). Absence of this fluctuation in the spectrogram in fig. 3 c) implies correlation between mode incidence and a significant runaway electron population.

Conclusions

Series of the high-frequency plasma eigenmodes from 150 kHz up to $f_{\text{Nyquist}} = 1$ MHz have been observed in the COMPASS tokamak plasmas by the magnetic diagnostics with an improved frequency coverage compared to the past work [3]. The eigenmode oscillations are present in both limiter and diverted plasmas, best visible on HFS and persist over L-H and H-L transitions. It was shown that their frequency follows Alfvén wave-like scaling described in [2, 5]. Moreover, discharges with RMP-induced plasma rotation braking suggest that the observed fluctuations rotate in the plasma-reference frame. Nonetheless, the driving mechanism of these oscillations is yet to be found. Discharges with increased runaway electron population contain chirping-character oscillations, which have frequency up to $f_{\text{Nyquist}} = 2.5$ MHz that follows Alfvén-wave-like dependency. Future work will focus at specification of toroidal and poloidal mode numbers of the oscillations and their radial localization, further studies of RMP field effect and simulations of Alfvén continuum spectrum and its gaps by the KINX code [8].

Acknowledgements

This study was supported by the projects GACR P205/12/2327, GACR 15-10723S and GA14-35260S and by grant RSF 14-22-00193.

References

[1] N.N. Gorelenkov, S. D. Pinches, K. Toi, Nucl. Fuison **54**, 125001 (2014)

[2] W.W. Heidbrink, Physics of Plasmas **15**, 055501 (2008)

[3] A.V. Melnikov, T. Markovic, L.G. Eliseev, et al., Plasma Physics and Controlled Fusion **57**, 065006 (2015)

[4] P. Cahyna, et al, Nucl. Fusion **49**, 055024 (2009)

[5] D.A. D'Ippolito, J. P. Goedbloed, Plasma Phys. **22**, 1091 (1980)

[6] S.E. Sharapov, 11th CMSS on Plasma and Fusion Energy Physics proceedings (2013)

[7] K. Kovařík, et al., 41st EPS Conference Proceedings, P5.025 (2014)

[8] S. Medvedev, et al., Computer Phys. Communications **103**, S0010-4655 (1997)