# Kinetic modelling of bifurcation conditions of resonant magnetic perturbations in ASDEX Upgrade experiments

M. Markl[1], P. Ulbl[2], C.G. Albert[1], C. Angioni[2], R. Buchholz[1],M.F. Heyn[1], S.V. Kasilov[1,3], W. Kernbichler[1], W. Suttrop[2] and the ASDEX Upgrade Team[4]

[1] *Fusion@ÖAW, Institut für Theoretische Physik - Computational Physics, Technische Universität Graz, Petersgasse 16, 8010 Graz, Austria*

[2] *Max Planck Institute for Plasma Physics, Boltzmannstraße 2, 85748 Garching, Germany*

[3] *Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", 61108 Kharkov, Ukraine*

[4] *See author list of U. Stroth et al. 2022 Nucl. Fusion 62 042006*

In this report, edge localized mode (ELM) suppression by resonant magnetic perturbations (RMPs) is investigated using the quasilinear kinetic model of Ref. [1]. There, Maxwell equations with kinetic plasma response currents are solved by the code KiLCA by modelling the tokamak as a straight cylinder. In this case, poloidal Fourier modes of the electromagnetic field perturbation are decoupled. An earlier method to include realistic device geometry from Ref. [1] has been improved in this report using the 2D ideal MHD code GPEC [2]. For a given mode, the resonant mode amplitude is adjusted by equating KiLCA and GPEC computed Fourier amplitudes of the parallel plasma response current integrated across the resonant layer. For shielded modes, which is the usual case when RMP amplitudes are infinitesimal, these integrals determine the jump in the tangential magnetic field across the layer and depend only weakly on the plasma response model. Small but finite RMP amplitudes induce radial transport (mainly of electrons) which can be described by quasilinear transport coefficients [1]. These coefficients are quadratic in perturbation field amplitudes and are strongly localized within resonant layers. Quasilinear transport by a particular RMP mode modifies the electron fluid velocity to bring its value at the mode-specific surface to the resonant value and the shielding becomes nearly absent. In MHD theory, the electron fluid resonance is present if the perpendicular electron fluid velocity is zero at the resonant magnetic surface. In kinetic theory, a finite shift between these two points is present in case of a finite electron temperature gradient. For a large enough RMP amplitude, rapid bifurcation to an unshielded state occurs, leading to the formation of magnetic islands and a plateau in the electron temperature profile near the resonant surface. It is commonly assumed [4] that such a bifurcation of an RMP mode that is resonant at the pedestal top correlates with ELM suppression.

First, we study possible bifurcations in ASDEX Upgrade (AUG) shot 33353 performed to optimize ELM suppression following the quasilinear evolution of plasma profiles governed by transport equations of Ref. [1]. There, the simplified anomalous transport model is based on a uniform single particle diffusivity so that all anomalous transport coefficients are simply related to the anomalous heat diffusion coefficient $D^{\mathrm{a}}$ which we set constant in time. The anomalous heat diffusion coefficient has been estimated from the electron heat balance and, for the particular time slice $t = 2.9$ s, computed by the code ASTRA. We start from the steady state profiles in absence of RMPs and linearly ramp-up the RMP coil current $I(t)$ to the experimental value $I_{\mathrm{expt}}$ reached within about $3s$. Bifurcation (loss of shielding) is detected if the radial magnetic field perturbation in the plasma $B_r^{\mathrm{plas}}(t)$ increases faster than linearly. An evolution of fluid resonances for the mode resonant at the pedestal top with $q = m/n = 6/2$ is presented in Fig. 1. Scans of $|B_r^{\mathrm{plas}}/B_r^{\mathrm{vac}}|$, where $B_r^{\mathrm{vac}}$ is the radial magnetic field perturbation in vacuum, over the drift velocity $\mathrm{v}_{E\times B}$ are shown for sets of plasma density and temperature profiles corresponding to different evolution times. Two equally important quasilinear transport mechanisms bring

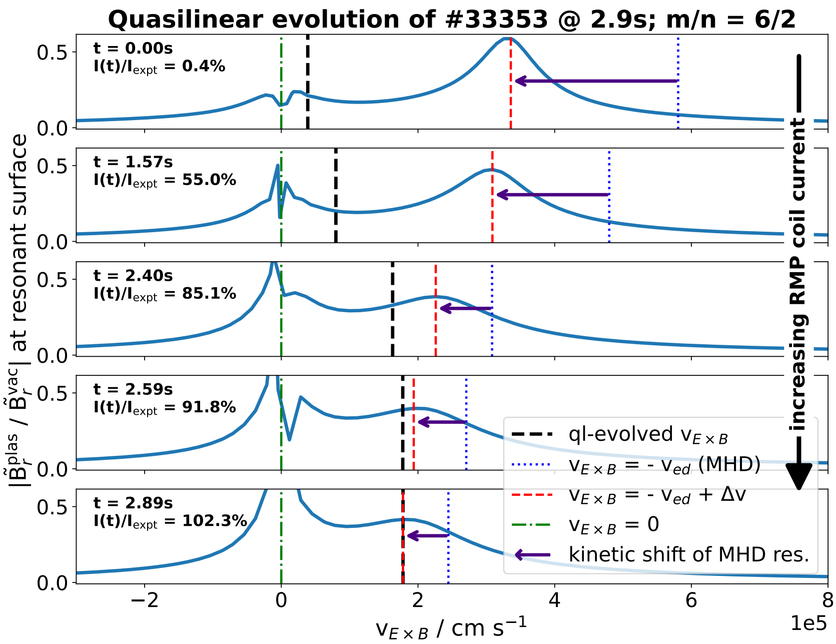


Figure 1: Quasilinear evolution of normalized resonant radial magnetic field as function of $\mathrm{v}_{E\times B}$ velocity for various normalized RMP coil current values $I(t)/I_{\mathrm{expt}}$. Vertical dashed lines mark $\mathrm{v}_{E\times B}$ values obtained within quasilinear evolution (black), and corresponding to electron fluid resonance in kinetic (red) and MHD (blue) models.

the evolved $\mathrm{v}_{E\times B}$ value to the electron fluid resonance. First, non-ambipolar particle transport results in a torque causing a global modification of $\mathrm{v}_{E\times B}$ and shifting it towards the fluid resonance. Second, electron heat transport tends to form a local plateau on electron temperature $T_e$ thus shifting the fluid resonance towards the gyrocenter resonance $\mathrm{v}_{E\times B} = 0$ and removing the difference between MHD and kinetic electron fluid resonances. Taken alone, the second mechanism leads to a bifurcation if the ratio of RMP-induced quasilinear electron heat diffusion coefficient and the anomalous coefficient exceeds unity at the resonant surface, $D^{\rm ql}_{e22}/D^{\rm a}\Big|_{r_{\rm res}} \geq 1$. Thus, this defines an approximate but numerically efficient criterion for the bifurcation threshold which we apply directly to experimental profiles without following the time evolution.

Due to a local plateau formation in $T_e$, bifurcation leads to the alignment of a resonant surface with the modified electron fluid resonance $\mathrm{v}_{e\perp} - c\partial_r T_e/(B_0 e) = 0$, i.e. with a reversal point of electron fluid velocity computed in absence of a $T_e$ gradient. The location of this resonance relative to resonant surfaces in shot 33353 is shown in Fig. 2a. After the onset of the RMP current

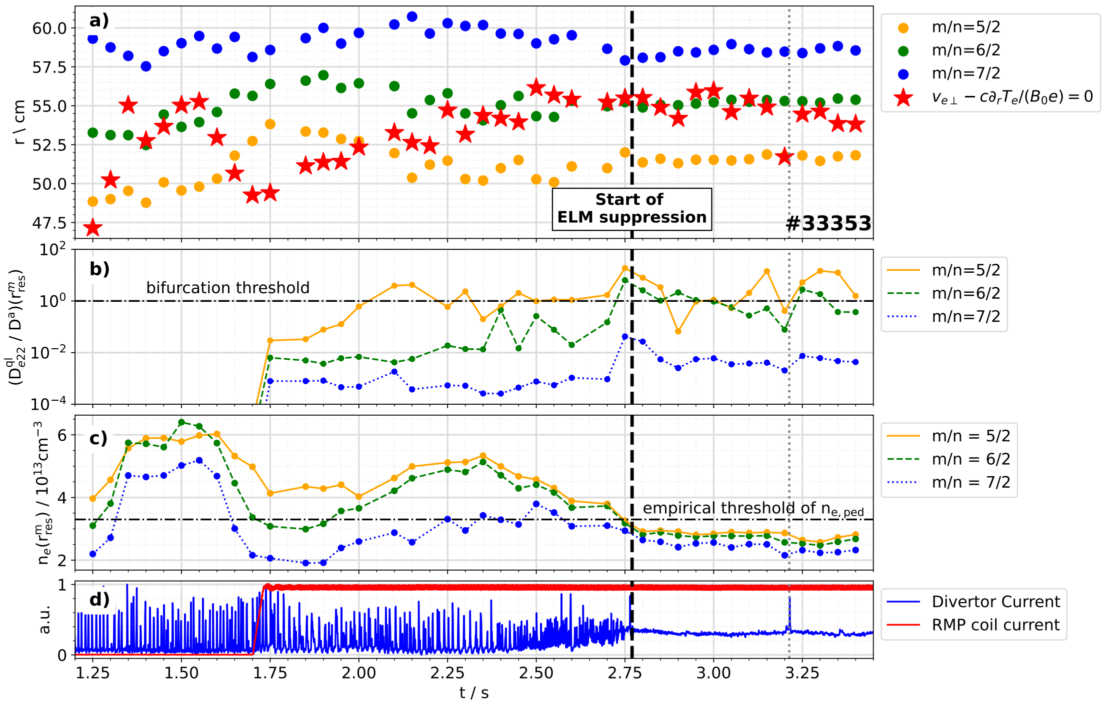


Figure 2: Plot of: a) relative location of modified electron fluid resonance to rational surfaces, b) approximate bifurcation criterion, c) electron density at the resonant surfaces and d) ELM relevant diagnostics for individual time slices during shot 33353 of AUG. ELMs are suppressed after $t = 2.77s$. A single ELM event occurs at $\sim 3.2s$ (grey dotted line). The empirical pedestal density threshold was taken from [3].

(Fig. 2d), the modified fluid resonance gets "captured" by the resonant surface $q = m/n = 6/2$. ELMs get then suppressed as soon as the density (Fig. 2c) decreases below a threshold value [3]. A jump in the approximate criterion (Fig. 2b) of mode $m/n = 6/2$ above the threshold just before the start of ELM suppression at $2.77s$ indicates bifurcation of this RMP mode. Mode $m = 7$ is already in the steep gradient region, where high rotation provides robust RMP shielding. Mode $m = 5$ is too far inside the plasma to be responsible for ELM suppression. An ELM event at $\sim 3.2$ s is preceded by a downwards trend of the approximate criterion below the threshold and a steeper density gradient, indicated by the spreading of the density values.

Calculating the approximate bifurcation condition for rescaled plasma profiles provides scaling relations of the bifurcation threshold. For the time slice $t = 2.9s$, we find that the RMP coil current threshold for bifurcating modes $m = 5,6,7$ scales with density as $I_{\mathrm{RMP}}^{\mathrm{thresh}} \propto n_e^{\alpha}$ with $0.6 < \alpha < 1.1$ including results of MHD modelling in Ref. [4]. In the two-dimensional parameter space in Fig. 3 we see that the experimental profiles lie in a "knee" structure representing the fluid resonance. Such a structure is not resolved by the MHD threshold determined in Ref. [4].

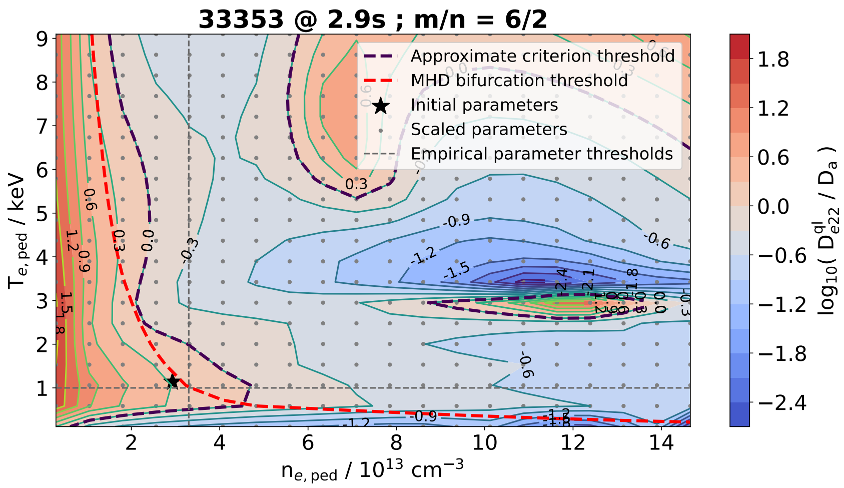


Figure 3: Scan of the approximate criterion in the density and electron temperature space, both taken at the pedestal. Empirical threshold limits from [3] are indicated by grey dashed lines. The red dashed line is the threshold scaling determined by the non-linear two-fluid code TM1 for DIII-D in [4] for profiles used in our case.

To conclude, using GPEC [2] to account for realistic device geometry in our cylinder model [1] allows us to qualitatively analyze ELM suppression by RMPs in AUG experiments. Within our modelling, we define a bifurcation criterion and a physically related modified electron fluid resonance. We find that ELM suppression in AUG shot 33353 correlates with the bifurcation of the RMP mode $m/n = 6/2$ resonant at the pedestal top where a capture of the modified fluid resonance occurs.

**Acknowledegments** 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. We gratefully acknowledge support from NAWI Graz and funding from the KKKÖ at ÖAW and the Friedrich Schiedel Stiftung für Energietechnik.

## References

[1] M.F. Heyn et al 2014 Nucl. Fusion **54** 064005

[2] J.K. Park and N.C. Logan 2017 Physics of Plasmas **24** 032505

[3] W. Suttrop et al 2018 Nucl. Fusion **58** 096031

[4] Q.M. Hu et al 2020 Nucl. Fusion **60** 076001