Investigating bifurcation of resonant magnetic perturbations in ASDEX Upgrade using an analytical criterion

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The suppression of edge localized mode (ELM) in H-mode tokamak plasmas is necessary for enabling a long-time operation of future reactor-sized devices, most prominently ITER. One experimentally verified method to suppress ELMs is by applying small magnetic field perturbations by an external coil system [2]. Usually, the plasma reacts to the external perturbation with shielding currents that essentially prevent the suppression. However, certain conditions enable the perturbation to penetrate and ELMs get suppressed. The penetration of an RMP mode that is resonant with a rational flux surface at the top of the H-mode pedestal is commonly associated with ELM suppression. Thus, a bifurcation, i.e. the penetration of a specific RMP mode while others are still shielded, is required.

In this report, we study the bifurcation of single RMP modes in with a criterion based on the linear and quasilinear kinetic model [3]. The linear Maxwell solver `KiLCA` employs a finite Larmor radius (FLR) expansion to calculate the kinetic plasma response current in the large aspect ratio limit. This limit allows for applying Fourier decomposition in toroidal as well as in poloidal direction with the caveat of losing poloidal mode coupling which is present in realistic geometry and can significantly influence the plasma response. The lack of mode coupling is corrected for by rescaling the calculated magnetic field perturbation by a form factor given by the ratio of shielding currents determined in `KiLCA` and the 2D ideal MHD code `GPEC` [1]. Further, the rescaled electromagnetic field perturbations are used to calculate quasilinear diffusion coefficients which govern the time evolution of plasma profiles in the one-dimensional quasilinear transport code `QL-Balance`. The slow linear ramp-up of the MP coil current of a single mode in the quasilinear time evolution eventually leads to the bifurcation of this mode. The bifurcation is enabled by two effects [3]. First, the radial electric field profile changes globally due to the MP-induced torque. Second, a local plateau forms in the electron density and temperature profiles. Both effects bring the value of the electron fluid velocity at the rational surface towards a resonance value enabling the breakdown of the shielding. The plateau formation is caused by the RMP-induced quasilinear transport quantified by the quasilinear diffusion coefficients.

Based on the plateau formation in the electron temperature, we define an approximate criterion indicating bifurcation as

$$\left.\frac{D^{\mathrm{ql}}_{e,22}}{D^{\mathrm{a}}}\right|_{r=r_{\mathbf{m}}} \geq 1, \tag{1}$$

where unity on the right-hand side is based on experience. Here, $D^{\mathrm{ql}}_{e,22}$ is the quasilinear heat diffusion coefficients of the electrons, which is the main driver of the plateau formation in the electron temperature and D^{a} is the anomalous diffusion coefficient coming from turbulence. Both are evaluated at the rational surface $r_{\mathbf{m}}$ in question where the safety factor $q(r_{\mathbf{m}}) = m/n$ is a ratio of the RMP-mode corresponding poloidal m and toroidal mode number n, here also written as $\mathbf{m} = (m,n)$. The quasilinear diffusion coefficient is calculated with the electromagnetic field perturbations, while the anomalous diffusion coefficient is calculated with a heat flux-based estimation [3], thus, possible dependencies on plasma parameters are not considered in D^{a}.

In constant-ψ approximation and in the limit close to the resonant surface, the quasilinear heat diffusion coefficient can be expressed in analytical form and the criterion becomes

$$\frac{D^{\mathrm{ql}}_{e,22}}{D^{\mathrm{a}}} \approx \frac{r^4_{De}}{4\pi r^4_{\mathbf{m}}} \frac{s^2 c^2}{|V^e_{\mathrm{res}}|^2} \left(1 + \frac{9\nu_e^2}{\pi^2 \omega_E^2}\right)^{1/2} \frac{279\nu_e^4 + 47\omega_E^2\nu_e^2}{9\nu_e^4 + 10\omega_E^2\nu_e^2 + \omega_E^4} \frac{k_z^2 \left|I^e_{m\|}\right|^2}{\nu_e D^{\mathrm{a}} B_0^2} \geq 1. \tag{2}$$

Here, r_{De} is the Debye length, s the magnetic shear, c the speed of light, V^e_{res} the fluid resonance velicity, ω_E the $E \times B$ rotation frequency, ν_e the electron collision frequency, k_z the toroidal wave number, B_0 the equilibrium magnetic field module and $I^e_{\mathbf{m}\|}$ the electron response current. The expression is independent of the ion species and does not in itself require the Maxwell solver `KiLCA`. Further, two resonance conditions appear. The electron fluid resonance

$$V^e_{\mathrm{res}} = V_{e\perp} - \frac{c}{2eB_0}\frac{\partial T_e}{\partial r} = 0,$$

with $V_{e\perp} = V_{ed} + V_{E\times B}$ being the electron fluid velocity composed of the diamagnetic velocity V_{ed} and the $E \times B$ velocity $V_{E\times B}$, e the electron charge, and T_e the electron temperature, as well as the gyrocenter resonance

$$\omega_E = k_\perp V_{E\times B} = -ck_\perp \frac{E_{0r}}{B_0},$$

where $k_\perp$ is the perpendicular wavenumber and E_{0r} is the equilibrium radial electric field which is calculated with the drift-kinetic equation solver `NEO-2` [3]. The former differs from the MHD-predicted resonance, $V_{e\perp} = 0$, in the presence of a finite electron temperature gradient which is also the case outside the constant-ψ approximation.

The model is applied to four ASDEX Upgrade shots which achieved ELM suppression after a period of ELM mitigation. The parameters of the shots, which are generally similar to one another, are summarized in table 1. The criteria (1) and (2) are determined for all shots after the MP coil current is turned on until some time into the ELM suppression phase. The time traces of the criteria (solid - numerical (1), shaded - analytical (2)) for modes $\mathbf{m} = (6,2)$ and $\mathbf{m} = (7,2)$, as well as the MP coil current and the divertor thermocurrent, can be seen in Fig.1. The shots are aligned with the beginning of the ELM suppression phase (dotted line). We find that the approximate analytical criterion provides a qualitatively similar picture as the numerical version in all cases. However, quantitatively, the constant-ψ approximation results in a smaller value in the majority of points. The approximation neglects the contribution due to the perturbation electric field which results in the overestimation of the shielding, in particular, for modes closer to the separatrix. Also, the radial magnetic field perturbation is generally not constant over the resonant layer but increases with radius, which becomes important for broad layers. Further, we find that the bifurcation criterion of mode $\mathbf{m} = (6,2)$ correlates with ELM suppression in shot 33353, while in the remaining shots, a correlation with ELM mitigation (green-shaded region) is observed. This is in contrast to the expectation to find a correlation of the criterion with the ELM suppression phase in all cases. Also, the experimental study in [2] suggests that mode $\mathbf{m} = (7,2)$ is the relevant one. However, this is not observed in our analysis. The reason for this discrepancy is yet unknown.

Table 1: Overview of ASDEX Upgrade shot parameters. B_t is the toroidal magnetic field, I_p the plasma current, q_{95} the edge safety factor, n_e the line-averaged density, κ the elongation, and δ_u (δ_l) the upper (lower) triangularity.

Shot	B_t/T	I_p/MA	q_{95}	$n_e/10^{19}\mathrm{m}^{-3}$	κ	δ_u	δ_l
33353	-1.792	0.900	3.600	6.47	1.772	0.299	0.474
33133	-1.790	0.900	3.603	4.90	1.726	0.284	0.477
34214	-1.821	0.885	3.710	5.98	1.737	0.302	0.469
34548	-1.802	0.900	3.586	4.98	1.732	0.267	0.479

The bifurcation of RMPs in four ASDEX Upgrade shots is investigated with a bifurcation criterion in numerical and analytical form. Despite the expectation to find a correlation with the ELM suppression phase, we observe that the criterion correlates with the ELM mitigation phase in three cases. Further steps are required to investigate the reason for this unexpected result and advance this study. For example, quantifying the uncertainties of our results will generally improve their significance. Also, the plasma response current is considered only in the leading order of the FLR expansion. Including higher orders may yield a different picture.

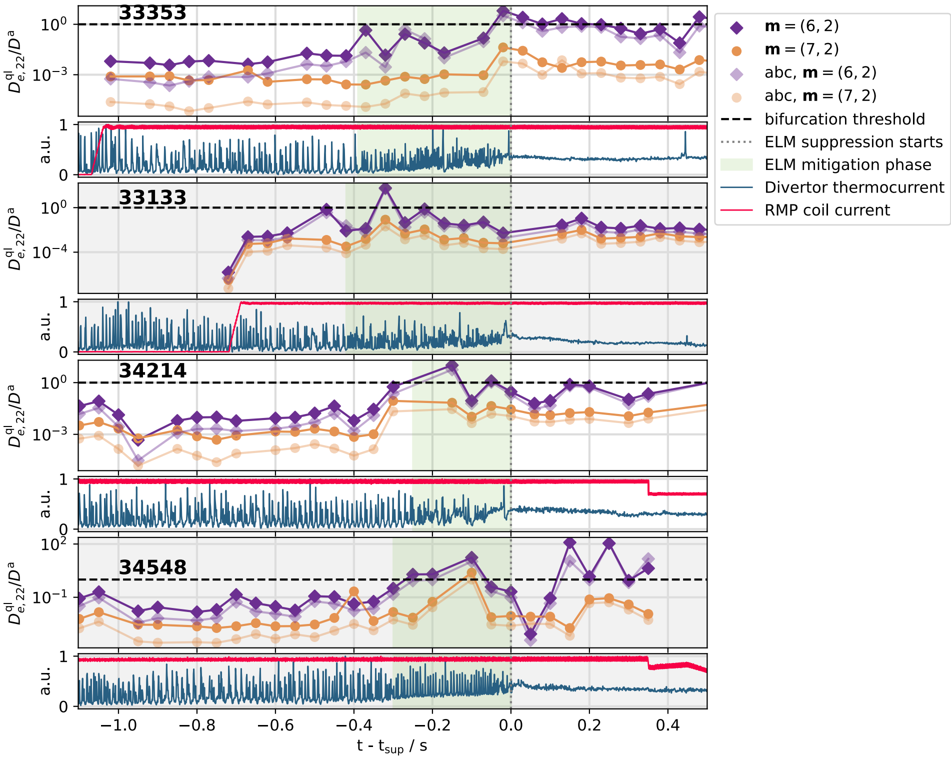

Figure 1: Comparison of the local bifurcation criterion during four ASDEX Upgrade shots. The numerical bifurcation criterion (solid) as well as the analytical bifurcation criterion (shaded) are plotted for modes $m = 6$ (purple) and $m = 7$ (yellow). Additionally, the MP coil current (red) as well as the ELM activity (blue) are plotted for each shot. The criterion correlates with the ELM mitigation phase (green shaded region) in shots 33133, 34214, and 34548, while shot 33353 correlates with the ELM suppression phase (vertical dotted line). The time traces are aligned with the beginning of the suppression phase, t_{sup}.

Extending the sample size by considering additional shots and possibly machines will provide further insights. Moreover, the impact of the anomalous diffusivity on the bifurcation criterion is unclear as it is based on an estimation scheme.

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