FUSION PLASMA PHYSICS

INTERPRETATION AND CONTROL OF HELICAL PERTURBATIONS IN TOKAMAKS

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The common research between the **Mathematical Modelling for Fusion Plasmas Group** of **the National Institute for Lasers, Plasma and Radiation Physics (NILPRP),** Magurele - Bucharest, Romania with the **Max-Planck - Institut für Plasmaphysik (IPP)**, Garching, Germany has been focalized on the following objectives:

1. Improvement of equilibrium calculations for stability analysis of modes in the separatrix vicinity in order to determine the influence of the plasma triangularity on the tearing mode stability parameter Δ' for the ASDEX-Upgrade tokamak.

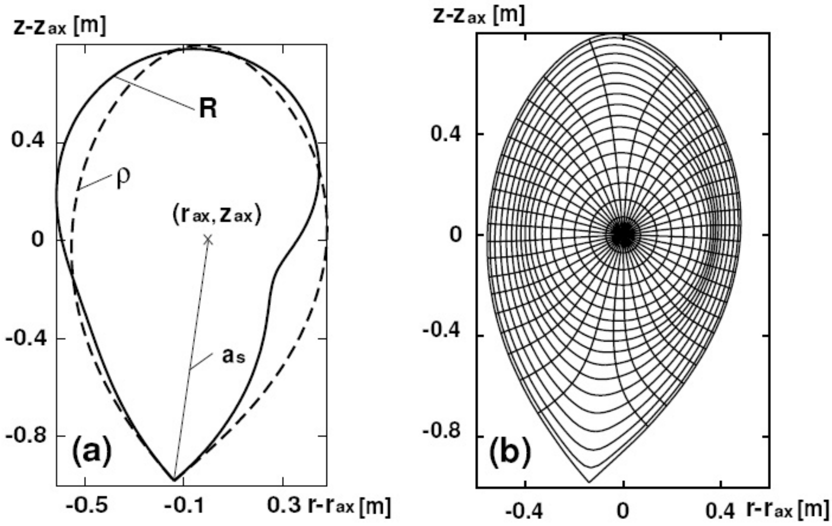
This objective has been finalized in 2004, after the decision taken together with our German partners in 2003 to continue it in order to have an estimation of the remaining stability energy when the unconditionally unstable neoclassical tearing modes occur.

The following **results** have been achieved:

a) Developing of analytical equilibrium solutions, able to describe a separatrix configuration

The "**cast function method**" [1] which describes diverted tokamak configurations has been improved. It is known that the separatrix breaks the structure of nested flux surfaces assumed in most flux coordinate systems and that the expansion in any orthogonal series, converge slowly near the X point. The developed cast function decreases the number of the essential moments for a diverted toroidal configuration permitting to obtain very accurate equilibrium solutions and solutions in real time [2]. In Figure 1 the cast function method is illustrated.

Observing that the metric coefficients obtained by an equilibrium solver are not smooth enough near the separatrix, the most complicated equilibrium solutions that can be obtained analytically has been found. A solution has been found, where for the first time, to our knowledge, the current density has a parameterization with 4 degrees of freedom, allowing the independent specification of: I_{pl}, β_p, l_i, q for both diverted and non-diverted configurations [3]. Analytical results obtained for a specific ASDEX-Upgrade discharge are given in Figure 2.



$$\rho(a,\omega) = R(a,\omega) + A_0(a) + \sum_{k=1}^{\infty}\left(A_k(a)\cos kt + B_k(a)\sin kt\right)$$

$$R(a,\omega) = a a_s\left[1 - \alpha_1(1-\cos t) + \beta_1 \sin t - \alpha_0\sqrt{\gamma(a-1)^2 + 1 - \cos t}\right]$$

Figure 1. Cast function method for the ASDEX-Upgrade separatrix (shot no. 5000 at 1.55 seconds). a) cast function R(a,t) exhibiting the same singularity at X – relative error =0.064% - 24 complex moments. ($t= \omega - \omega X$, $a \in [0,1]$, as, α1, α0, β1 are geom. parameters, γ is a free parameter. b) Constant a and ω lines.

b) Interpretation of different experimental discharges of the ASDEX-Upgrade tokamak from the Δ' (the tearing mode stability parameter) point of view.

Different experimental discharges (advanced scenario) of the ASDEX Upgrade tokamak have been considered from the stability parameter Δ' point of view for tearing instabilities with different wave numbers m/N. Taking the shot no. 13476 at 5.2 seconds as reference, we have investigated the influence of the triangularity, the ellipticity and the aspect ratio on Δ'. The obtained results, presented in Figure 3, show the increasing of the stability with triangularity δ and ellipticity κ as well as the decreasing of the stability with the aspect ratio. Three different tearing modes have been considered: m/N=2/1, 3/2 and 4/3 (m and N are the poloidal and toroidal wave numbers) [2].

This work has been carried out in close collaboration with our German colleagues from the Tokamak Physics Department of the Max-Planck-Institut für Plasmaphysik, during the mobility 02.05.04-30.07.04 at IPP Garching and at our home institute NILPRP.

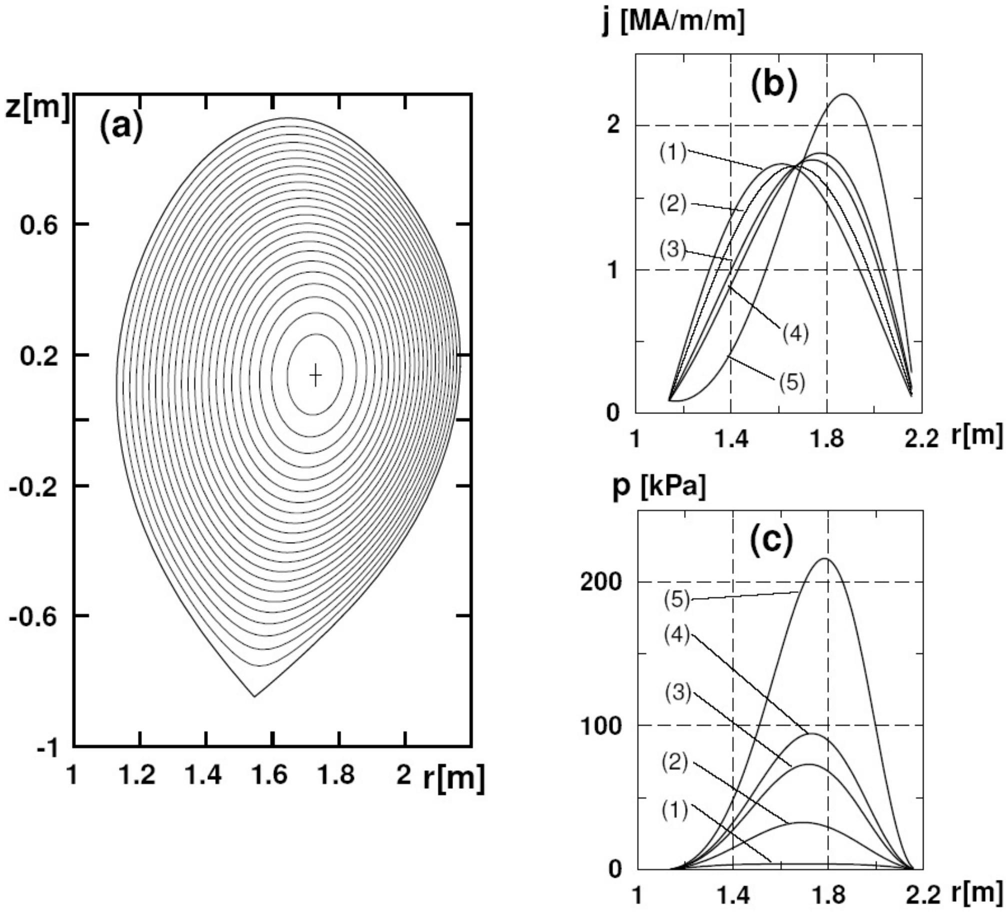


Figure 2. Equilibrium parameters for the discharge No. 5000 at 1.55 s of the ASDEX Upgrade tokamak at different poloidal betas. a) constant flux lines, b) current density profiles at $z=z_{ax}$, c) pressure profiles at $z=z_{ax}$.

2. <u>Plasma Models for feedback control of helical perturbations</u>

The goal of our common research is to advance the physics understanding of the Resistive Wall Modes (RWM) stability, including the dependence on plasma rotation, wall/plasma distance, and active feedback control, with the ultimate goal of achieving sustained operation at beta values close to the ideal-wall beta limit through passive or/and active stabilization of the RWM. With this in view, the aim of the present work was to find an optimal feedback system needed for stabilizing resistive wall mode instabilities in a large-aspect, low-beta tokamak plasma. Two models of the RWMs have been considered:

- a **2D semi-analytic model** consisting of the cylindrical approximation model with arbitrary poloidal and "toroidal" disposals, i.e. without symmetries, of wall, feedback and detector systems. In this model the dissipation of plasma rotation via anomalous viscosity can be taken into account;

- a **2D numerical model** consisting of a real axisymmetrical tokamak model with arbitrary cross-section and plasma parameters, and with symmetric poloidal and toroidal disposals of wall, feedback and detector systems.

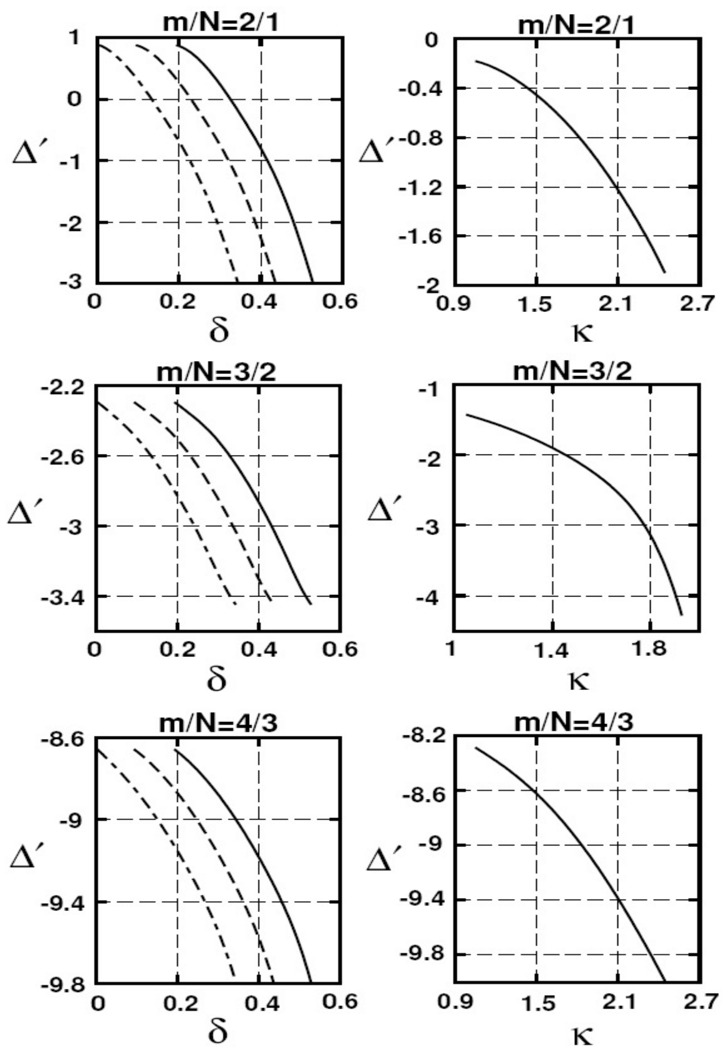


Figure 3. Δ' dependences on triangularity δ and ellipticity κ for ASDEX Upgrade (shot no. 13476 at 5.2s)

Up to now, the basics of the first model have been developed [4], with the following achieved **milestones**:

- improving the performance of our analytical model by considering a symmetrical disposal of both feedback coils along the poloidal direction and walls along the equivalent toroidal direction;
- investigation of the influence of the relative position of the detector with respect to the wall on the growth rate of the RWM in order to found an optimum stabilization, with consideration of plasma rotation and plasma viscosity;
- investigation of the influence of the poloidal angular extent of the feedback coils with respect of the wavelength of the considered plasma RWM.

The construction of our analytical calculus consists in its final step in solving an algebraic equation whose degree is an increasing function of the number of the plasma modes taken into account. Numerical difficulties have appeared, especially concerning considerable amounts of time necessary to perform the calculus, due to the non-symmetric poloidal disposal of the detectors and coils around the plasma. For the case of an active feedback system with poloidal symmetry we have derived a simplified analytical treatment of RWM, allowing us to partially decouple plasma modes as a consequence of poloidal symmetry. Therefore, we have obtained a system of partially decoupled equations leading to algebraic equations in plasma modes growth rate with smaller degrees. The RWM taken into account is coupled only with plasma modes whose poloidally mode number is a sum of RWM's poloidal number and a multiple of the number of poloidally disposed feedback coils. This fact allowed us to perform calculations with an increased number of plasma modes and, as a consequence, a better description of the RWM's behaviour.

The following obtained results have to be underlined [4]:

1) compared with the numerical results provided by the CASTOR numerical code used at IPP, we have found the same result: with the detector coil placed below the passive shell the stabilization of the RWM is improved. But then we found a new important fact - the neighbouring plasma modes begin to increase their own growth rates. This result could not be found by the numerical code. Therefore, our results have shown that placing the detector below the shell has a destabilizing effect for sideband or plasma modes involved in calculus.

2) we have found that the angular extent of the feedback coils is important in order to stabilize the RWM, in the sense that the extent of the coil must equal the half-integer multiple of the wavelength of the plasma mode in the case when feedback coils are disposed symmetrically. Our results showed also that the coupling between RWM and adjacent plasma modes is smaller when the above condition is accomplished.

Note that these results were possible by founding in our previous formulation of the standard Leibniz development relation (permitting a maximal number of Fourier terms of eight only) some symmetry properties (translated in the possibility of introducing some “delta” Kronecker functions) giving us the possibility to use ~80 sideband harmonics, obtaining thus a good convergence in the Fourier development.

In the Figure 4 different dependencies of the growth rate of the (3,1) RWM for m=1,…,6; n=1,...,2; a=1m (small radius) have been presented [3]; R_0=6m (big equivalent radius); q_a=2.9 (safety factor at the boundary); q_0=1.3 (safety factor at the axis); $\eta_{wSS}=7.23*10^{-7}$ Ωm (stainless steel resistivity); $\eta_{wAl}= 2.7*10^{-8}$ Ωm (aluminium resistivity); $\Delta\theta_f=\pi/6$ (poloidal angular distance between feedback coils); $\Delta\theta_d=\pi/9$ (poloidal angular between detectors); G_d=31 V/Wb (differential amplification factor); G_p=5.5 V/V (proportional amplification factor); Ω_θ=0 rot/s (poloidal plasma rotation); Ω_Φ=-14000 rot/s (toroidal plasma rotation); B_{za}=2.1T (toroidal magnetic field); r_f=1.25m (radius of the feedback coils); r_d=1.35m (radius of the detectors); $\mu_{visc}=9*10^{-14}$kg/m/s (plasma viscosity); θ_{coils}= [0, π/6, π/3, π/2,3π /2,5π /3,11π /6] (poloidal angular location of the feedback coils).

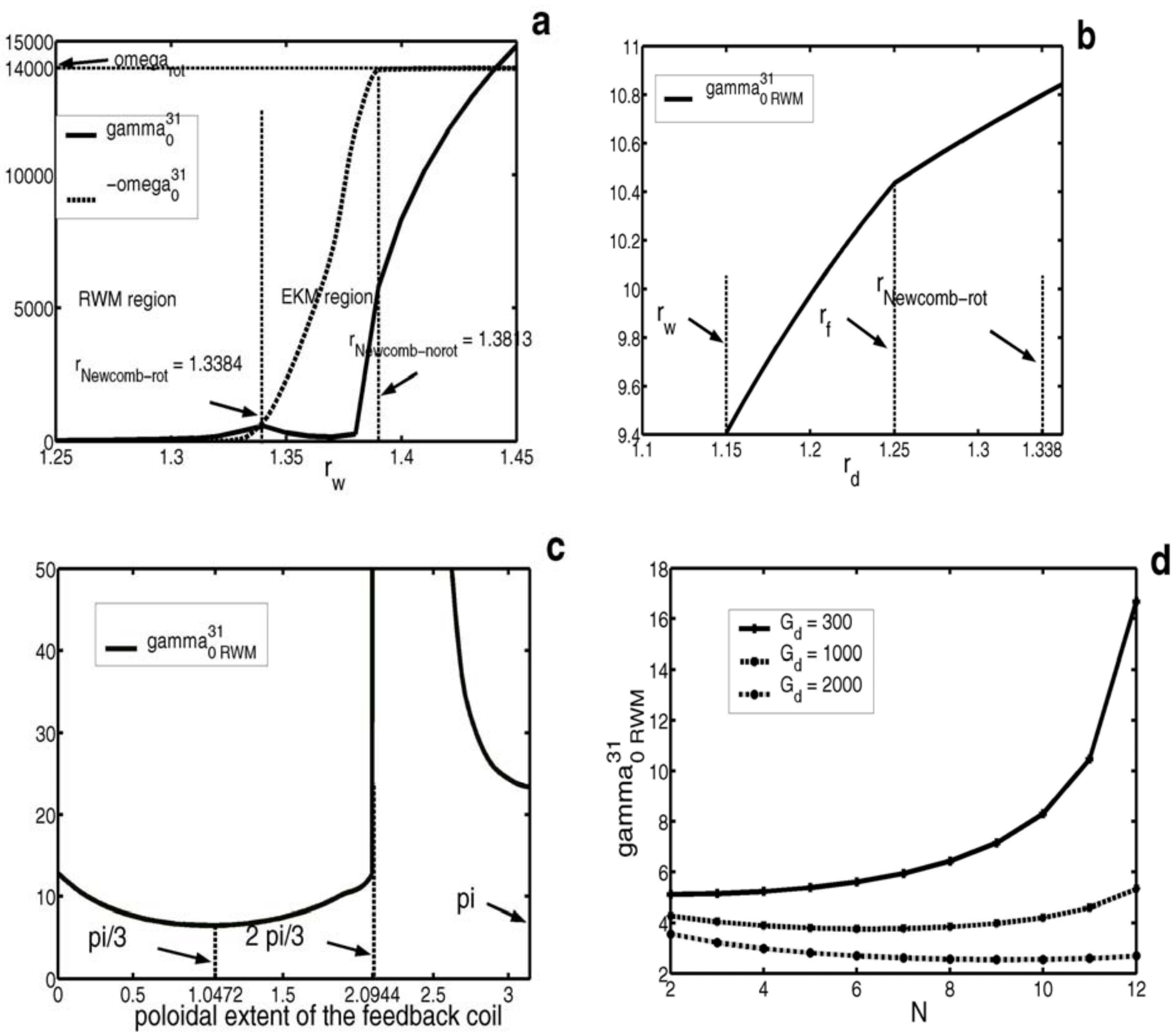


Figure 4. Growth rate dependencies in the considered resistive wall mode

In Figure 4a the growth rate and the real frequency of the (3, 1) RWM mode as a function of the radius of the resistive shell is presented. The destabilizing effect of approaching the critical Newcomb radius (the radius where the modulus of the flux function perturbation vanishes) and especially the critical Newcomb radius with no rotation of the edge plasma is showed. When the radius of the shell is placed above the critical Newcomb radius with no rotation of the plasma edge, the RWM cannot be stabilized, its own frequency preserving the value of the rotation of the plasma edge itself. Figure 4b presents the stabilizing effect of placing the sensor coil of the active feedback system as near as possible to the position of the passive shell surrounding the plasma. Figure 4c shows the growth rate of the (3/1) RWM, plotted as a function of the poloidal angular extent of feedback coils for the case in which there are four evenly coils in the poloidal direction. It can be seen that the feedback system is has no stabilizing effect whenever the poloidal extent of the feedback coil is equal to the poloidal wavelength of the unstable mode. The RWM is stabilized when the poloidal extent of the feedback coil is equal to the half poloidal wavelength of the RWM. Figure 4d presents the stabilizing effect of the increase of the amplification factor induced in the feedback system by the sensor coil. The growth rate of the RWM is plotted against the toroidal number of the feedback coils disposed toroidally symmetric.

This work has been carried out in close collaboration with our German colleagues from the Tokamak Physics Department of the Max-Planck-Institut für Plasmaphysik, during the mobility 22.12.04-19.03.05 at IPP Garching and at our home institute NILPRP.

In a **next step** the following milestones will be considered:

- investigation of the influence of the position, dimensions and resistivity of the feedback system on the growth rate of the RWM;
- investigation of the influence of the plasma rotation relative to the shell on the behaviour of the RWM in the presence of the feedback system;
- calculation of the minimum rotation of the plasma inertial layer required for the stabilization of the RWM.
- study of the influence of the anomal viscosity as dissipation mechanism of the plasma rotation on the stabilization of the RWM;
- description of the influence of the cumulative effect of plasma rotation and coupling between RWM and eddy currents induced in the passive shell surrounding the plasma;
- calculation of the coupling effect between the RWM and adjacent modes on the RWM growth rate and its rotation.

Publications:

[1] **Atanasiu C. V., Moraru A., Subbotin A.,** *"Improvement of the moments method for equilibrium calculation in a deverted tokamak configuration",* Computer Physics Communications 98, 137 (1996).

[2] **Atanasiu C. V., Günter S., Lackner K., Moraru A., Zakharov L.E., Subbotin A. A.**, *"Linear tearing modes calculation in diverted tokamak configurations"*, Physics of Plasmas 11, 5580 (2004).

[3] **Atanasiu C. V., Günter S., Lackner K., Miron I. G.**, *"Analytic solutions to the Grad-Shafranov equation"*, Physics of Plasmas 11, 3510 (2004).

[4] **Atanasiu C. V., Miron I. G., Günter S., Lackner K.**, *"Stabilisation of resistive wall modes"* (submitted at the 11th European Fusion Theory Conference, Aix-en-Provence, 2005).